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14. ABSTRACT
The primary goal is to develop a novel, efficient, integrated, subsurface monitoring system, capable of capturing transient chemical plumes in real-time to assess the source and predict future plume behavior. This proof-of-concept research aimed at demonstrating the use of an intelligent Wireless Sensor Network (WSN) to monitor contaminant plume movement in naturally heterogeneous subsurface formations to advance the sensor networking based monitoring for decision making and design. Also of specific interest in the demonstration using

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Wireless Sensor Network Based Subsurface Contaminant Plume Monitoring

ABSTRACT

The primary goal is to develop a novel, efficient, integrated, subsurface monitoring system, capable of capturing transient chemical plumes in real-time to assess the source and predict future plume behavior. This proof-of-concept research aimed at demonstrating the use of an intelligent Wireless Sensor Network (WSN) to monitor contaminant plume movement in naturally heterogeneous subsurface formations to advance the sensor networking based monitoring for decision making and design. Also of specific interest in the demonstration using synthetic data and date from test aquifers, was how we can adapt computational transport models to utilize data from the WSN and how well this improves model predictions to be used in intelligent remediation. Experimental research was conducted in 2-D and 3-D test aquifers. The data generated in these synthetic aquifer instrumented with sensors and motes was used to validate developed software, inversion methods and modeling tools. A study, which focuses on the periodic inclusion of concentration data into a computational advection-dispersion transport model was performed using a synthetic data set and real data generated in the 3-D test aquifer. Virtual Sensor Networks (VSNs) algorithms that potentially will enable sensor network to be coupled to plume transport model when managing large number of sensors was developed.

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Received	Paper
2012/04/30 1 12	Iñigo Urteaga, Kevin Barnhart, Qi Han. REDFLAG: A Run-timE, Distributed, Flexible, Lightweight, And Generic fault detection service for data-driven wireless sensor applications, Pervasive and Mobile Computing, (10 2009): 0. doi: 10.1016/j.pmcj.2009.08.001
2012/04/30 1 11	Philip Loden, Qi Han, Lisa Porta, Tissa Illangasekare, Anura P. Jayasumana. A wireless sensor system for validation of real-time automatic calibration of groundwater transport models, Journal of Systems and Software, (11 2009): 0. doi: 10.1016/j.jss.2009.05.049
2012/04/11 1 9	H. M. N. Dilum Bandara, Anura P. Jayasumana, Tissa H. Illangasekare. A Top-Down Clustering and Cluster-Tree-Based Routing Scheme for Wireless Sensor Networks, International Journal of Distributed Sensor Networks, (01 2011): 0. doi: 10.1155/2011/940751
2012/04/11 1 2	K. S. Barnhart, T. H. Illangasekare. Automatic transport model data assimilation in Laplace space, Water Resources Research, (01 2012): 0. doi: 10.1029/2011WR010955
2012/04/11 1 3	Lisa Porta, Tissa H. Illangasekare, Philip Loden, Qi Han, Anura P. Jayasumana. Continuous Plume Monitoring Using Wireless Sensors: Proof of Concept in Intermediate Scale Tank, Journal of Environmental Engineering, (09 2009): 0. doi: 10.1061/(ASCE)EE.1943-7870.0000045
2012/04/11 1 10	Kevin Barnhart, Iñigo Urteaga, Qi Han, Anura Jayasumana, Tissa Illangasekare. On Integrating Groundwater Transport Models with Wireless Sensor Networks, Ground Water, (09 2010): 0. doi: 10.1111/j.1745-6584.2010.00684.x

TOTAL: **6**

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Porta, P., Illangasekare, T.H, Loden, P, Q.Han, Liptak, D and Jaysumana, A. 2007. Continuous Plume Monitoring and Model Calibration using a wireless sensor network: Proof of Concept in Intermediate-Scale Tank Test, AGU Hydrology Days, March, Ft Collins, Co, March 2007.

Porta. L., Illangasekare, T.H., Loden, P and Han, Q., 2007. Wireless Sensor Network Based Continuous Plume Monitoring: Proof Of Concept In Intermediate-Scale Tank Test, Geological Soc. of America, Denver, Colorado, Oct 07.

Barnhart, K.,Iñigo Urteaga, Qi Han, Lisa Porta, Anura Jayasumana, Tissa Illangasekare, "Combining Wireless Sensor Networks and Groundwater Transport Models: Protocol and Model Development in a Simulative Environment," AGU Fall Meeting, Oral Presentation, December, 2007, San Francisco, California.

Barnhart, K.S., D.W. Dean, T.H. Illangasekare, "Modeling Fingering at a Continuum Scale: A Stochastic Lagrangian Approach," American Geophysical Union Hydrology Days, Poster Presentation, March 2007, Fort Collins, Colorado.

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

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2012/04/11 1'	8	Anura P. Jayasumana, Tissa Illangaskare, Toshihiro Sakaki, Qi Han. A wireless sensor network based closed-loop system for subsurface contaminant plume monitoring, Distributed Processing Symposium (IPDPS). 2008/04/13 02:00:00, Miami, FL, USA. : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Received		Paper
2012/04/11 0:	1	Kevin Branhart, Imigo Urteaga, Qi Han, Anura Jaysumana, Tissa Illangasekare. On Integrating Groundwater Transport Models with Wreless Sensor Network, Ground Water (12 2008)

TOTAL: 1

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Books

Received		Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Illangasekare (2007-2011)

- Elected to the Board of Trustees of the Consortium of Universities for Advancement of Hydrologic Sciences (CUAHSI), 2008.
- Elected by peers as the Vice-Chair of the Gordon Research Conference on Flow in Permeable Media to be held in 2010 and Chair to be held in 2012.
- Semi-finalist, National Security Science and Engineering Faculty Fellowship (NSSEFF), Department of Defense, 2010.
- Honorary Doctorate in Natural Science and Technology, Uppsala University, Sweden, 2010.
- Recipient of Colorado School of Mines Senate Excellence in Research Award, August 2010.
- Hydrology Award, American Geophysical Union, Hydrology Days, Colorado State University, Ft. Collins, Colorado, March 2011.

. Member, National Academy/ National Research Council Committee on the Future Options for Management in the Nation's Subsurface Remediation Effort, 2010-2011.

- Member, National Academy/ National Research Council Committee on Opportunities And Challenges For International Science at the U.S. Geological Survey , 2010-2011.

Jayasumana

Keynote speech, "Sensor Networks: Bridging the Physical and Digital Worlds," CUAHSI-HMF Hands-on Workshop on Distributed Sensing: Taking it to the field , Boulder CO July 16-18, 2008 (CUAHSI: Consortium of Universities for the Advancement of Hydrologic Science, Inc.)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Lisa Porta	1.00	
Kevin Barnhart	1.00	
Dilum Bandara	1.00	
Paul Schulte	0.25	
FTE Equivalent:	**3.25**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Tissa Illangasekare	0.10	
Anura Jaysumana	0.10	
FTE Equivalent:	**0.20**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Lisa Porta	
Paul Schulte	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Kevin Barnhart	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Statement of the problem studied

A recent projection from the U.S. Environmental Protection Agency (EPA) states that as many as 350 thousand contaminated sites will require cleanup over the next 30 years, costing $180-$280 billion (EPA, 2004). The same report estimates that out of these sites, 6,400 are Department of Defense (DoD) sites, costing approximately $33B. Of these sites, approximately 3,000 require cleanup of chlorinated solvents. A 2004 National Research Council (NRC) report discussed the U.S. Army's Installation Restoration Program, stating that 88% of the over 11,000 sites managed by the Army have reached "remedy-in-place/response completed," requiring long term monitoring options. For both current and "remedy-in-place" sites, monitoring is very costly. Considering these factors, this research focused on the development of a new monitoring technology for rapid and real-time remediation performance assessment with the ultimate goal of remediation optimization for cost reduction.

The primary goal of the project is to develop a novel, efficient, integrated, subsurface chemical plume monitoring system, capable of capturing transient plumes in real-time to assess the source and predict future plume behavior. This research on proof-of-concept technology development is aimed at demonstrating the use of an intelligent, self-organizing Wireless Sensor Network (WSN) to monitor contaminant plume movement in naturally heterogeneous subsurface formations to advance the sensor networking based monitoring technology for decision making and design. Also of specific interest, is how we can adapt computational transport models to utilize data from the WSN and how well this improves model predictions.

Summary of the most important results

- We have developed a basic test platform to test and evaluate the feasibility of data collection for monitoring of three-dimensional transient subsurface plumes using wireless sensors. We have deeloped and installed the basic software necessary for remote data acquisition. Several experiments have already been conducted using this testbed. The results for the first tank packing experiments show good qualitative data for tracer breakthrough curves in the tank and close reproducibility of experiments. The second packing experiments carefully examined the accuracy of sensing data as compared to traditional sampling results and evaluated different sensor calibration methods for use in data conversion from pore water electrical conductivity to solute concentration. Two main conclusions were made: 1) Ion Chromatography data analysis helped to validate the qualitative nature of the conductivity data already observed in the first experiments, and established that the sensing data are also quantitatively useful for tracking a plume. 2) The ex-situ and in-situ calibration curves are different, with sensing data lying outside of the ex-situ calibration curve. Traditional sampling data are useful for obtaining an in-situ adjusted calibration curve for the sensors.
- We have desgined and constructed a large-scale laboratory tank. This tank has the ability to create large interesting plumes for the WSN to detect, it can also run experinments that last one or two weeks, allowing sufficient time for data to be processed and for the computational transport model to be updated in real-time.
- We have installed mote devices in tank for wireless data collection and experimental testing of WSN protocols.

- We have developed a methodology for transport model calibration employing macro-scale dispersivity and plume transport time as the objective function observation metrics.
- We performed a study which focuses on the periodic inclusion of concentration data into a computational advection-dispersion transport model. We found that Even small amounts of erroneous data may significantly affect the outcome of the calibrated model, Transport model forecasts are highly sensitive to parameter estimation input variables, particularly regularization parameters. Model agreement generally improves with each iteration of data assimilation even when most previous data has been eliminated through data reduction. Predictions of transport fate only remain valid for short time periods after model calibration despite the increase in data.
- We have designed a new method for WSN data assimilation. Instead of using concentration data, we used the frequency information from the breakthrough curve profiles in our parameter estimation process. This guarantees faster and more reliable model inversion.

- We have developed the conceptual architecture for Virtual Sensor Networking (VSN), which allows some of the nodes in the network (e.g., those immersed in the plume) to collaborate on sensing, detecting, and tracking tasks. We have also developed communication suppot for forming and maintaining VSNs. In particular, we developed and evaluated a generic top-down clustering algorithm for sensor networks that not only forms clusters in a controlled manner, but also organizes the clusters into a tree during the cluster formation process. Scalability of the algorithm makes it suitable for large-scale field deployments.
- We have further extended the generic top-down clustering algorithm by making use of the Receiver Signal Strength Indicator (RSSI) available in most wireless devices to reduce its overhead, enhance its configurability, and to support realistic wireless environments.
- We have developed a cluster tree based routing mechanism and two extensions to facilitate communication with the base station (node-to-sink) as well as within the network (node-to-node). These routing schemes are useful in forming, maintaining, and communicating within and across VSNs under different scenarios.
- We developed an algorithm that forms a VSN by connecting nodes observing the same phenomenon through a virtual tree. We developed a mechanism to deliver unicast and multicast messages within and across VSNs.

- We desgined a closed loop system to deliver sensed data to the processing center (which executes transport models) and carry commands from the processing center (based on the predicted plume behavior) back to the sensor nodes. We demonstrated that our approach could significantly reduce energy consumption in applications that track rapidly migrating, merging, and splitting phenomena such as hazardous gases.
- We have developed a software tool for deployment in the WSN thathelps to detect sensor and network faults as they occur. This service, called REDFLAG, has low overhead and is highly adaptable to a myriad of WSN scenarios.
- We have developed a novel methodology for including concentration values in parameter estimation: by performing transport model inversion in the Laplace domain. This is partly possible because data gathered by WSNs is known densely in time. While not all problems may be easily solved in the Laplace domain, this new method may be suitable when computational time is a concern such as in situations involving real-time decision making. An intermediate scale synthetic aquifer was used to illustrate the proposed technique. This research presents a new paradigm in model use, application and validation.

The appendix and the papers provide more details asscietd with these findings.

Technology Transfer

Wireless Sensor Network Based
Subsurface Contaminant Plume Monitoring

Appndix to Final Report

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1. Introduction

The primary goal of the project is to develop a novel, efficient, integrated, subsurface chemical plume monitoring system, capable of capturing transient plumes in real-time to assess the source and predict future plume behavior. This research on proof-of-concept technologydevelopment is aimed at demonstrating the use of an intelligent, self-organizing Wireless Sensor Network (WSN) to monitor contaminant plume movement in naturally heterogeneous subsurface formations to advance the sensor networking based monitoring technology for decision making and design. Also of specific interest, is how we can adapt computational transport models to utilize data from the WSN and how well this improves model predictions.

This final report is organized as follows. Sections 2 and 3 briefly outline the work done in the first two years of the project. Section 4 summarizes the progress made in the last year and this work is detailed in Section 5. Project conclusions and suggestions for future work are given in Section 6.

2. Summary of 2006-2007 findings

To achieve the stated goals, we have worked on two specific tasks during the year 2006/07. First, we have developed a basic test platform to test and evaluate the feasibility of data collection for monitoring of three-dimensional transient subsurface plumes using wireless sensors. The testbed consists of ten sensor nodes, each equipped with conductivity sensors (ECH$_2$O TE probes manufactured by Decagon Devices, Inc). These sensors were selected after researching different sensors available in the market, based on their compatibility with our accuracy and cost requirements. We developed the required hardware and software and interfaced these to TelosB wireless sensor networking modules from Crossbow Technologies. These nodes are placed in a tank of size 244 cm long × 44 cm in hight, which was used for in-situ measurement. The basic software necessary for remote data acquisition has been developed and installed. Several experiments have already been conducted using this testbed.

Second, we have developed the conceptual architecture for Virtual Sensor Networking (VSN), which allows some of the nodes in the network (e.g., those immersed in the plume) to collaborate on sensing, detecting, and tracking tasks. The architecture relies on underlying networking protocols to support connectivity among members of the VSN. Currently we are working on development of such protocols, focusing on routing algorithms capable of supporting VSN functionality in large-scale plume tracking networks. Several alternative approaches are being investigated. One of them relies on imposing a cluster hierarchy on the sensor field; we developed and evaluated a top-down clustering algorithm that can be used for this purpose (Bandara and Jayasumana 2007).

2.1 Summary of experimental results

The results for the first tank packing experiments show good qualitative data for tracer breakthrough curves in the tank and close reproducibility of experiments. No modeling analysis was conducted at this time, because not all the equipment was ready for accurate data collection. Equipment-related issues (sensor failure) were identified, pointing out some of the weaknesses of this system. System failure has major implications for field applications. If half the sensors deployed in the field do not respond, much time needs to be devoted to discovering the reason for failure. More personnel would be needed and cost would increase. However, it is anticipated that these issues will be resolved over time, once environmental WSNs are more robust and reliable. For initial deployments, sensor choice and calibration are major considerations that need to be well understood in the laboratory before larger-scale applications.

The second packing experiments carefully examined the accuracy of sensing data as compared to traditional sampling results and evaluated different sensor calibration methods for use in data conversion from pore water electrical conductivity to solute concentration. Two main conclusions were made:

1. Ion Chromatography data analysis helped to validate the qualitative nature of the conductivity data already observed in the first experiments, and established that the sensing data are also quantitatively useful for tracking a plume.
2. The ex-situ and in-situ calibration curves are different, with sensing data lying outside of the ex-situ calibration curve. Traditional sampling data are useful for obtaining an in-situ adjusted calibration curve for the sensors.

It was observed that the poor resolution of the sensors did not permit a very accurate calibration curve to be obtained. Sensor calibration data approximationsresult in inaccuracies when sensing data are converted to concentration data. Thus,sensing data give a better temporal resolution than traditional sampling data but with a lower quality of results. Nonetheless, sensing technology proves valuable for subsurface monitoring since user involvement is minimal and for more accurate results grab samples can be taken at critical times. This sampling system is not very robust yet: sensor and mote failure have been observed and prohibit reliable data collections over longer periods of time. This is a major problem in the field. Much needs to be done in order to develop a better system to be employed in the field.

2.2 Summary of distributed algorithms for self-organization, data collection, and plume detection

Our objective is to develop the communication infrastructure that can effectively support large-scale subsurface plume monitoring systems. Power conservation, self-organization of nodes, routing, and management are some of the fundamental and critical issues in such large-scale sensor deployments. Research dealt with two essential components required for self-organization and data collection:

- Development of a Virtual Sensor Network (VSN) architecture
- Clustering and cluster-tree formation in wireless sensor networks

First step was to develop the concept of virtual sensor networking as the basis for self-organization in plume tracking networks. A Virtual Sensor Network (VSN) is formed by a subset of sensor nodes of a Wireless Sensor Network (WSN), with the subset dedicated to a certain task (such as detecting or tracking a plume) at a given time. This contrasts with traditional dedicated sensor networks, in which all the nodes in the network collaborate more or less equally to achieve the end result. In contrast, the subset of nodes belonging to the VSN collaborates to carry out a given application while remaining nodes provide support functionality (e.g., relaying of data and control messages). A chemical plume is a 3-D transient phenomenon that is spatially and temporally distributed, and which evolves in its intensity and extent. It is different from a phenomenon that is time varying in a fixed region (e.g., temperature/humidity changes in a room), or a phenomenon that varies in locations but not extents (e.g., mobile object). For instance, plumes can change their configuration/shape as a result of not only migration but also due to remedial treatment. Therefore,it is important to build a communication infrastructure that can effectively extract and deliver data under migrating, splitting, merging, and disappearing plumes. VSN provides a self-organization mechanism to combine sensors detecting the same phenomenon into a logical network and allow them to communicate with each other effectively. The VSN architecture is detailed in (Jayasumana, Han, and Illangasekare 2007). We have also identified two additional classes of applications, beyond plume tracking, for which the proposed VSN architecture is applicable. One of the classes consists of geographically overlapped sensor networks, and the other consists of sensor networks that utilize multifunctional sensor nodes, where a node may sense different phenomenon at different times.

Providing communication support for forming and maintaining VSNs is a key research challenge. Several approaches have been identified for providing communication support for VSN. We have focused on one such approach based on organizing the sensor field as a set of clusters. With clustering, the nearby nodes in a network are grouped into set of administrative entities called *clusters* and each cluster is managed by a designated node called the *cluster head*. A key requirement for efficiency of this approach is the ability to build uniform clusters in a distributed manner. We developed and evaluated a generic top-down clustering algorithm for sensor networks that not only forms clusters in a controlled manner, but also organizes the clusters into a tree during the cluster formation process. The algorithm is configurable, forms uniform and circular clusters, and a cluster tree with a lower depth. Scalability of the algorithm makes it suitable for large-scale field deployments. (Bandara and Jayasumana 2007) provides initial result, including variation of tree depth that could be obtained, a comparison of circularity of clusters produced by two different approaches, etc. thus providing a glimpse of the capabilities of the generic top-down clustering algorithm. Research is continuing on characterizing several different cases of the algorithm targeted toward VSN for plume tracking.

3. 2007-2008 accomplihments and findings

Much progress has been made in 2007/2008. Upon review, we have accomplished all of the goals we proposed in 2006/2007progress report. It is also encouraging that much of

the work done in 2007/2008 came to fruition within the last year, as we were able to lay the groundwork for more advanced experiments and analysis.

This project received much recognition in the second year, including the following:

- H. M. N. D. Bandara completed an M.S. in Electrical and Computer Engineering on "Top-down clustering based self-organization of collaborative wireless sensor networks."
- L. Porta completed an M.S. in Environmental Science and Engineering on "Continuous plume monitoring and model calibration using a wireless sensor network: Proof of concept in intermediate-scale tank test."
- Three refereed conference papers in Electrical and Computer Engineering related conferences (Bandara, H. M. N. D. and A. P. Jayasumana 2007; Bandara, H. M. N. D., A. P. Jayasumana, and T. Illangasekare 2008; Bandara, H. M. N. D., A. P. Jayasumana, and I. Ray 2008).
- A conference paper and presentation on "Integration of Groundwater Transport Models with Wireless Sensor Networks" (Barnhart, K., I. Urteaga, Q. Han, A. Jayasumana, and T.Illangasekare 2008). This paper was given the distinction of "Best Student Abstract."
- A poster by H. M. N. D. Bandara, "A Wireless Sensor Network Based System for Underground Chemical Plume Tracking," won the first place at Colorado State University ISTeC Student Research Poster Contest, 2008. The Poster is available via http://digitool.library.colostate.edu/.
- A presentation was given at the Fall American Geophysical Union meeting 2007 titled "Combining Wireless Sensor Networks and Groundwater Transport Models: Protocol and Model Development in a Simulative Environment" (Barnhart, K., I. Urteaga, Q. Han, L. Porta, A. Jayasumana, and T. Illangasekare 2007).

3.1 Summary of WSN Experimentation and Use of WSN Data in Models

Experimental work conducted in an intermediate scale test system during the 2006/2007 year elucidated several challenges for using WSNs to monitor subsurface contaminants:

1. Long-term sensor and network reliability is questionable;
2. There are discrepancies between in-situ and ex-situ calibrations for the chosen EC sensors. Additionally, values do not directly correspond to grab samples that have been analyzed by Ion Chromatography equipment.
3. Automatically updating the transport model parameters as new data becomes available was not successful.

Appropriately, a majority of our effort in 2007/2008 focsed on addressing these issues.

The Decagon ECH$_2$O TE sensors used in the initial 2006/2007 experiment showed visible corrosion. Additionally, their resolution was quite coarse. We relayed these concerns to Decagon's R&D department and they have provided us with new ECH$_2$O5TE sensors that are more resistant to corrosion and have been specially programmed to have more sensitivity in the range that we desire. Preliminary results from small-scale experiments suggest that the new sensors will work for our large-scale laboratory tank experiment.

Given that the WSN and sensors will be exposed to potentially harsh outdoor environments, some sensor and network failure is expected to occur. We anticipate that vendors will continue to improve the robustness of their products. In the meantime, we developed a software tool for deployment in the WSN thathelps to detect sensor and network faults as they occur. This service, called REDFLAG, has low overhead and is highly adaptable to a myriad of WSN scenarios.

We obtained the new ECH_2O 5TE for testing purposes in July, 2008. We have performed small-tank experiments in a homogeneous sand packing where the sensors are placed in mini PVC wells. Using wells not only better mimics field deployment techniques, but also allows for easy removal/storage of the sensors (the experiments in the previous report buried the sensors directly). Basic tracer experiments were conducted with NaBr and we analyzied grab samples in an attempt to obtain an empirical, but quantitative relationship between the EC reading by the sensor and the actual concentration of NaBr outside of the well. The hope is that this will help us build a procedure for using both in-situ/ex-situ calibrations and grab samples to lend reliability to WSN data.

We have made some preliminary progress in the area of automatically updating computational transport model parameters as data arrives from the WSN. In contrast to the initial attempt in the previous year, we are evaluating our methods using synthetic data (initially) to control purposes. We have also begun to use the freely available commercial package PEST instead of UCODE. PEST, especially the newer versions, has many advanced parameter estimation tools not available in UCODE; one in particular is the ability to use regularization, which better allows us to deal with data noise. Some initial findings were published in the conference: MODFLOW and More 2008: Groundwater and Public Policy. Since then, we have created a 3D data set based on a real field site with which we will conduct 3D simulations this Fall.

Finally, due to the limitations of the original intermediate-scale laboratory tank experiment, we have designed and begun constructing a large-scale laboratory tank. This new tank has several realistic advantages, including:

1. the ability to create large interesting plumes for the WSN to detect;
2. the inclusion of mini wells in which to place the sensors and take pressure and grab samples; and
3. running experiments that last one or two weeks, allowing sufficient time for data to be processed and for the computational transport model to be updated in real-time.

3.2 Summary of WSN clustering, routing, and Virtual Sensor Network Algorithms

During 2007/2008year, we continued to further explore the cluster based organization of the sensor field because of its desirable characteristics that are capable of supporting Virtual Sensor Networks (VSNs). Research dealt with following components required for self-organization and data collection:

- Extended the generic top-down clustering algorithm to reduce its overhead, enhance its configurability, and to support realistic wireless environments
- Formation of a secure backbone based on the cluster tree for secure communication
- Development of several routing schemes to deliver data within the sensor network and to the base station
- Development of a self-organization scheme for VSNs
- Extension of the routing schemes to facilitate inter-VSN and intra-VSN communication

We further extended the generic top-down clustering algorithm (Bandara and Jayasumana 2007) to reduce its overhead, enhance its configurability, and to support realistic wireless environments. The enhanced algorithm forms geographically distributed set of clusters, has a lower overhead, and reduces collisions within the wireless network. The enhanced algorithm can make use of the Receiver Signal Strength Indicator (RSSI) available in most wireless devices. RSSI is a suitable metric to determine relative distances among nodes. By utilizing RSSI, it is possible to form a spatially distributed set of clusters with better properties such as circularity and uniform coverage. Two-step post cluster and cluster tree optimization phase is proposed to increase the connectivity of the network and to further reduce the depth of the cluster tree. (Bandara 2008) provides an extensive performance analysis of the top-down clustering algorithm, use of RSSI, and cluster and cluster tree optimization phase. These extensions provide an even better solution than the original algorithm proposed in 2006/2007.

Intrusion prevention and secure delivery of sensor data within the network is important in certain mission critical WSN applications. In plume tracking, it is important to prevent an attacker form generating false alarms and causing remediation systems to misbehave. Generic top-down clustering algorithm has been extended to build a secure communication backbone based on the cluster tree with minor modifications. The secure backbone formation algorithm and performance analysis is presented in (Bandara, Jayasumana, and Ray 2008).

A cluster tree based routing mechanism and two extensions are developed to facilitate communication with the base station (node-to-sink) as well as within the network (node-to-node):

1. Cluster tree based routing
2. Cross-links based routing
3. Circular-paths based routing

These routing schemes make use of the cluster tree formed by the generic top-down clustering algorithm (Bandara and Jayasumana 2007; Bandara 2008). Cross-links based routing and circular-pathsbased routing are extensions of cluster tree based routing. A hierarchical addressing scheme that reflects the parent-child relationship of cluster heads is used to route data along the cluster tree. This addressing scheme significantly reduces the complexity of the routing algorithm and requires very little amount of routing

information to be stored at a cluster head. These routing schemes are useful in forming, maintaining, and communicating within and across VSNs under different scenarios. Cross-links based routing can deliver 2.1-2.4 times more messages within the sensor field while circular-paths based routing delivers 5.2-6.4 times more messages delivered (Bandara 2008; Bandara and Jayasumana 2009).

We developed an algorithm that forms a VSN by connecting nodes observing the same phenomenon through a *virtual tree*. Nodes that detect a relevant phenomenon try to self-organize themselves by indicating their interest to form/join a VSN to others that detects the same phenomenon. We make use of the cluster tree formed with our generic top-down clustering algorithm and routing schemes to deliver VSN formation/discovery messages and to communicate within and across VSNs. A virtual tree marked on top of the cluster tree is used to interconnect such nodes. Our VSN formation scheme has a much lower overhead and guarantees that two or more nodes observing the same phenomenon are going to meet with each other compared to random routing schemes such as Rumor Routing (Braginsky and Estrin 2002), Zonal Rumor Routing (Banka, Tandon, and Jayasumana 2005), and Ant Routing (Hussein and Saadawi 2003). Simulation based results are used to confirm that our scheme works better than Rumor Routing (Bandara, Jayasumana, and Illangasekare 2008). We developed a mechanism to deliver unicast and multicast messages within and across VSNs. Cross-links and circular-pathsbase routing schemes are much more useful in delivering messages across different VSNs and within a VSN that is geographically distributed. (Bandara, Jayasumana, and Illangasekare 2008) provides initial results on VSN formation scheme while extensive performance analysis is presented in (Bandara 2008; Bandara and Jayasumana 2009).

Though clustering algorithm, secure backbone formation algorithm, routing schemes, and VSN formation algorithm are designed for the plume tracking application these algorithms/schemes are applicable for broad class of problems. These schemes are scalable hence suitable for actual field implementations.

4. 2008-2009 accomplishments and findings

4.1 Summary of Laboratory Test Bed and Computational Modeling

The work of Porta (2007), which was a precursor to this investigation, was hampered by failures in sensors that were imbedded in a laboratory scale sand tank. It was recommended that future studies use well emplacement of sensors to allow for sensor maintenance and replacement when necessary. Also, to better explore the WSN's communication potential, a recommendation was made that a large, lab-scale, three-dimensional test facility be developed. This "synthetic aquifer" test bed would allow for the creation of complex two or three dimensional contaminant plumes in a controlled laboratory environment. It would also provide a test bed for development of WSN technology. Finally, the synthetic aquifer would facilitate proof of concept validation of an integrated system which: employs a WSN to autonomously collect solute transport

data, screen the data for anomalies, and conduct real-time automatic calibration of contaminant transport models.

New applications in sensors and wireless networks are continually becoming available as underlying technologies become more efficient and robust. As yet, the full potential of applying WSN technology in the field of subsurface hydrology has considerable opportunity for development. One area to be explored is the direct integration of sensor data into groundwater and contaminant transport models. The ability to perform this integration in a wireless, automated manner will be a considerable advancement in technology, allowing for improved site characterization and plume tracking at costs that should be lower than conventional means. In support of this vision of an integrated system, the present study accomplished the following goals:

- Design and construct a large lab-scale synthetic aquifer capable of acting as a WSN research and development test bed. The synthetic aquifer has control mechanisms enabling the creation of complex plume geometries.

- Develop a methodology for transport model calibration employing macro-scale dispersivity and plume transport time as the objective function observation metrics.

The following tasks enabled the achievement of these goals:

Task 1) Conduct detailed design and construction of the synthetic aquifer facility.
Task 2) Perform numerical modeling of synthetic aquifer design proposals. Develop operation curves to categorize flow properties based on aquifer fill material.
Task 3) Develop a custom sensor configuration based on the expected plume characteristics. Ascertain calibration coefficients for each sensor.
Task 4) Develop experimental plume configurations through the use of numerical models
Task 5) Conduct laboratory testing of aquifer flow and tracer plume transport.
Task 6) Calculate temporal moments and macro-scale longitudinal dispersivity from time series sensor data.
Task 7) Determine the grid-scale dispersivity and effective porosity through inverse modeling.
Task 8) Install mote devices in tank for wireless data collection and experimental testing of WSN protocols.

4.2 Summary of Virtual Sensor Network Based Closed Loop System

We demonstrated the ability of virtual sensor networks to meet the application requirements of subsurface plume tracking by simulating a closed loop system. The closed loop system was designed to deliver sensed data to the processing center (which executes transport models) and carry commands from the processing center (based on the predicted plume behavior) back to the sensor nodes. Such commands include *sample faster*, *sample slow*, *sample now*, etc. We used synthetic data to simulate two migrating plumes over a three year period (Barnhart 2008). Sensor nodes that detect a plume were self-organized into a VSN according to the cluster tree based VSN formation scheme

developed in 2007/2008 (Bandara, Jayasumana, and Illangasekare 2008; Bandara 2008). Nodes that are in the VSN, i.e., already detecting the phenomenon, were configured to sample once a day while other nodes were configured to sample once every two weeks. Such a long sampling interval is desirable as plumes migrate very slowly and in the mean time nodes cansave energy by sleeping. Based on the predicted migration pattern of the plume, non-VSN nodes were added to the VSN and configured to sample faster to enable consistent tracking of the plume. We simulated the migration of the two plumes on a 2500m×2000m sensor field with 1000 sensors. For the given setup, simulation results showed that our VSN based approach was able to reduce the overall energy consumption of the network by 37% compared to a traditional WSN. Formation of a cluster tree based VSN also ensured that VSN members can always send/receive messages to/from the processing center, through other VSN members, during their active periods. Therefore, the processing center was able to get a consistent view of the plumes at every sampling interval. Ability to increase sampling rate based on the predicted behavior of plumes allowed us to track the plume with better spatial and temporal resolution. We further demonstrated that our approach could significantly reduce energy consumption in applications that track rapidly migrating, merging, and splitting phenomenonssuch as hazardous gases.

These results are encouraging and confirm the appropriateness of cluster tree based virtual sensor network formation in large-scale subsurface plume monitoring systems. Though clustering algorithm, secure backbone formation algorithm, cluster tree based routing schemes, and VSN formation algorithm are designed for the plume tracking application these algorithms/schemes are applicable for broad class of problems. Those schemes are also scalable hence suitable for actual field implementations. We believe contributions of this research will have a much more profound impact in future collaborative and large-scale WSNs.

5. Details of 2008-2010 findings

This section provides some details of the work completed in the last year.

5.1 Laboratory Test Bed and Computational Modeling

Previous WSN studies conducted in the CSM-CESEP facility pointed to the need for a large, laboratory-scale test bed to conduct two or three dimensional solute transport experiments. This test bed facility would come to be referred to as the CESEP synthetic aquifer. The size, and corresponding weight, envisioned for this facility were well beyond standard two dimensional vertical wall laboratory sand tanks. It was desired that the synthetic aquifer have a large planview area allowing for significant longitudinal travel distance and transverse migration. Physical limitations of laboratory floor space and the ability to work on and around the synthetic aquifer were also important factors influencing the facilities design.

Figure 1 is a photograph of the synthetic aquifer in operation. The overall waterproof "tank" section is 8 feet (2.438 meters) wide by 16 feet (4.877 meters) long and can be filled to a depth of 22.5 inches (0.5715 meters).

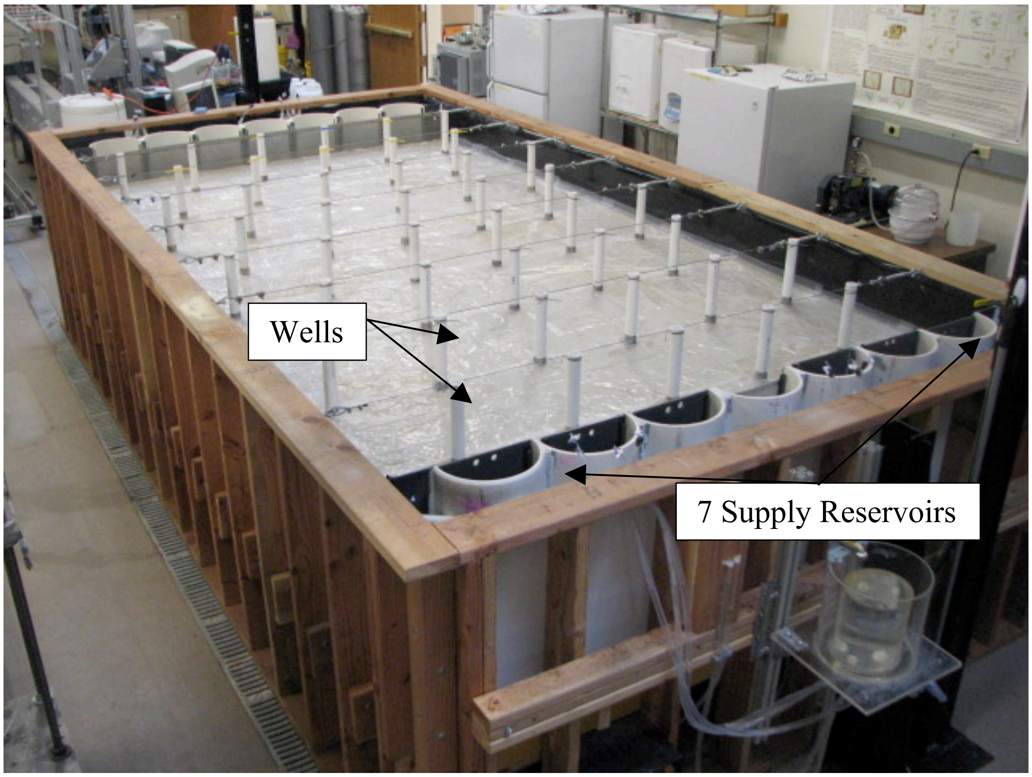

Figure 1: The CSM-CESEP Synthetic Aquifer facility. Overall tank dimensions are 8x16 feet with a maximum fill depth of 22.5 inches.

Aquifer inlet and outlet flow was controlled by the addition of 7 supply and 7 drain reservoirs as seen in Figure 1. Each reservoir could be fully opened or closed to flow by either a slid-in gate or by a valve which shut off the water flow to or from the reservoir. This controllable reservoir system enabled the creation of complex 2 dimensional subsurface flow patterns. Reservoirs are identified as S1-S7 and D1-D7, with S1 being nearest the observer in Figure 1 and D7 at the far corner of the synthetic aquifer.

The synthetic aquifer porous media field is comprised of a homogeneous lab-quality, #70 sieve size sand. The field contains 44 fully penetrating wells arranged in a staggered pattern of 8 rows. Wells were constructed of 1-1/4 inch PVC pipe which was capped, perforated and covered with a high density stainless steel mesh as seen in Figure 2. The well distribution pattern within the aquifer is depicted in Figure 3; reservoir centerline locations are also shown.

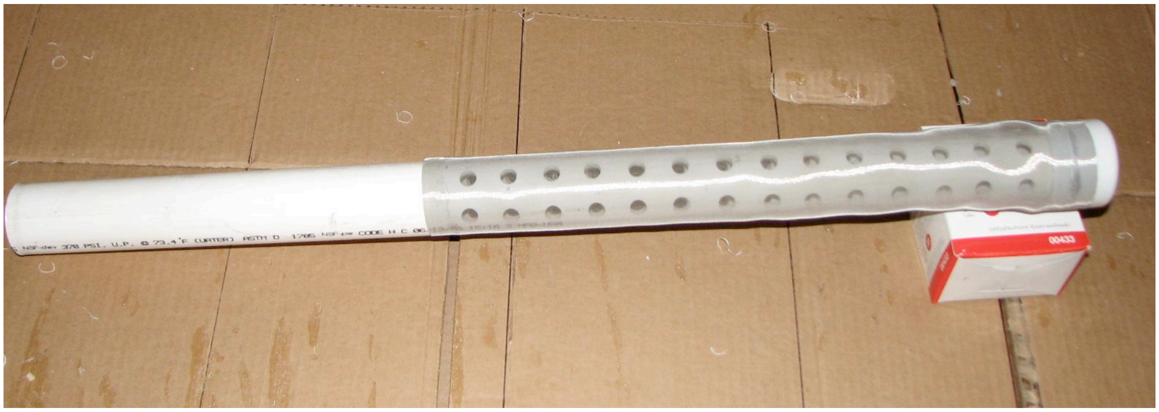

Figure 2: Construction of a synthetic aquifer well.

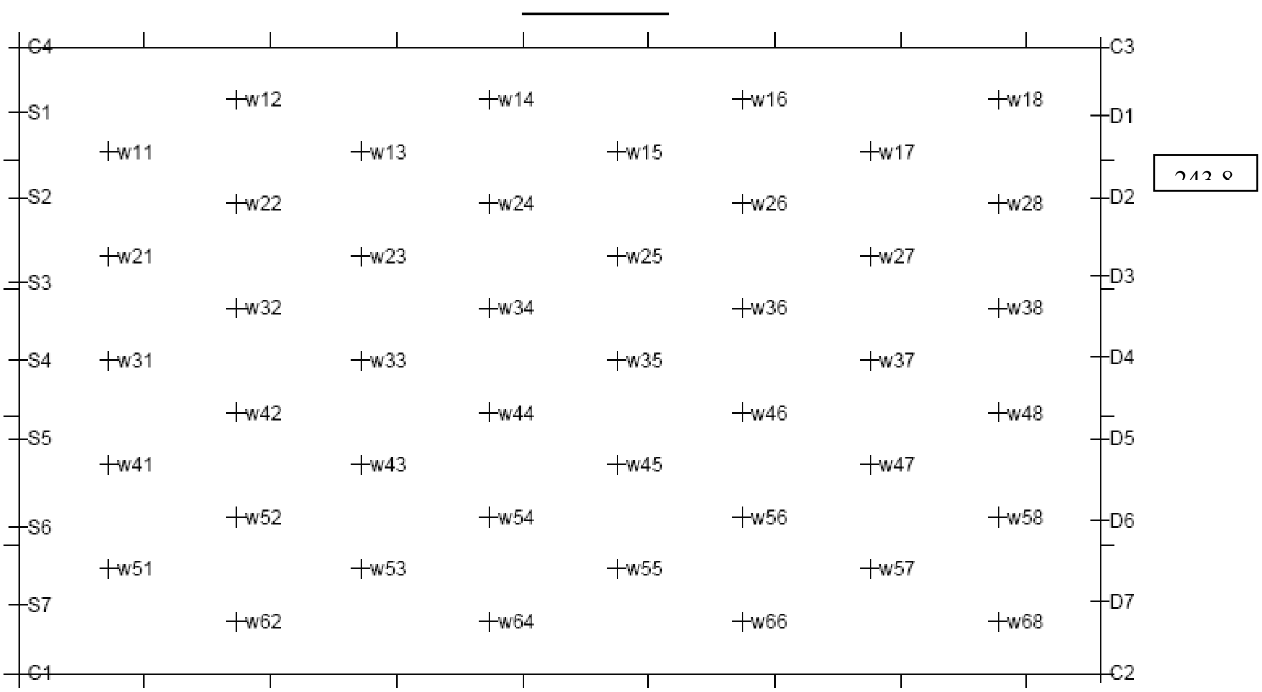

Figure 3: Schematic of well placement in the synthetic aquifer. Well rows are spaced 52.1 cm and transverse well spacing is 41.9 cm (centerline to centerline).

Electrical Conductivity Sensors

The Decagon Devices Inc. 5TE sensor was selected for this investigation to measure solute concentrations from sodium bromide electrolyte tracer plumes. The Decagon 5TE sensor, seen in Figure 4, is designed to measure soil moisture, subsurface temperature, and bulk electrical conductivity. These sensors are constructed for robust operation in harsh subsurface environments. The inclusion of a temperature reading allows the sensor

to fully temperature compensate the electrical conductivity measurements. Circuitry internal to the sensor processes the measured data and provides a calibrated, digital response. For this work, sensor excitation and data acquisition was accomplished by plugging the 5TE sensors into Decagon Devices model EM50 dataloggers.

Figure 4: Decagon Devices Inc. 5TE Soil moisture, temperature, and electrical conductivity sensor.

Monitoring of the sodium bromide electrolyte tracer was to be carried out by measuring the electrical conductivity of the water traveling through the synthetic aquifer. Therefore the Decagon 5TE electrical conductivity sensors needed to be calibrated to tracer concentration. Thirty-eight (38) total sensors were available for this investigation and each one was calibrated to provide unique fitting parameters relating the sensors measured electrical conductivity to a sodium bromide aqueous concentration. Six (6) dilution sets were created using Millipore $_{TM}$ laboratory-grade water as the base solution. Each dilution set began as a unique 10,000 mg/L NaBr concentrate. Each of these concentrated solutions was then diluted to create calibration standards of 100, 500, and 1000 mg/L NaBr. An initial calibration set of 20, 100, 250, 500, 1000, and 2000 mg/L NaBr was used to calibrate the first 6 electrical conductivity (EC) sensors and determine if a linear relationship existed between measured conductivity and NaBr aqueous concentration. Figure 5 is a plot of the results from this initial calibration study. It shows that a linear calibration scheme is appropriate to relate measured conductivity to expected NaBr concentration. It also pointed to the fact that each sensor has its own calibration slope and zero offset intercept, therefore requiring a unique calibration be conducted for each sensor.

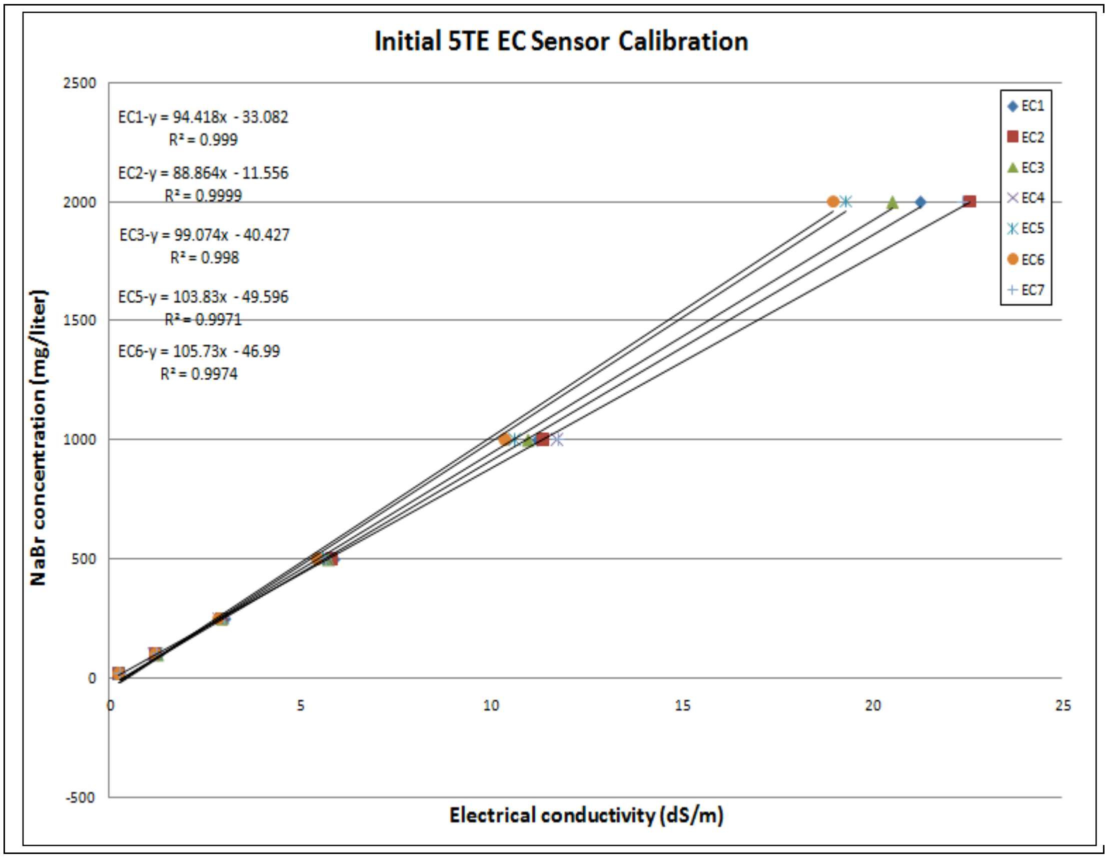

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Figure 5: Initial calibration of first 6 EC sensors.

Numerical Modeling and Comparison to Sensor Measurements

Numerical modeling of the synthetic aquifer was an integral part of this investigation from the beginning. Subsurface head and flow analysis was conducted using the simulation software MODFLOW-2000 and tracer transport was modeled using the code MT3DMS. Inverse modeling and calibration of the flow models was conducted using UCODE-2005, calibration of the transport models.

Having constructed the tank, it was then necessary to advance it into a synthetic aquifer capable of creating plumes relevant to WSN technology development. Numerical modeling was used to investigate any actions prior to employing them on the physical synthetic aquifer. The following tasks were accomplished:

- packing the synthetic aquifer
- performing flow experiments of several configurations to check aquifer operation
- comparing flow models to experimental flow measurements
- calibrating flow models based on experimental observations
- creating complex plume configurations which test WSN and real-time model calibration capabilities.

Figures 6 and 7 compare the numerical and physically measured plume concentrations for the baseline plume. The baseline plume was constructed by opening all 7 supply and 7 drain reservoirs to flow and releasing a 1000 mg/L NaBr tracer into the centerline supply reservoir (identified as S4).

The next plume generated was designated the “diagonal” configuration. It was constructed by opening all 7 supply reservoirs and only the D7 drain reservoir to flow. Figures 8 and 9 compare concentrations obtained from numerical transport modeling and concentrations measured with EC sensors located in the synthetic aquifer wells.

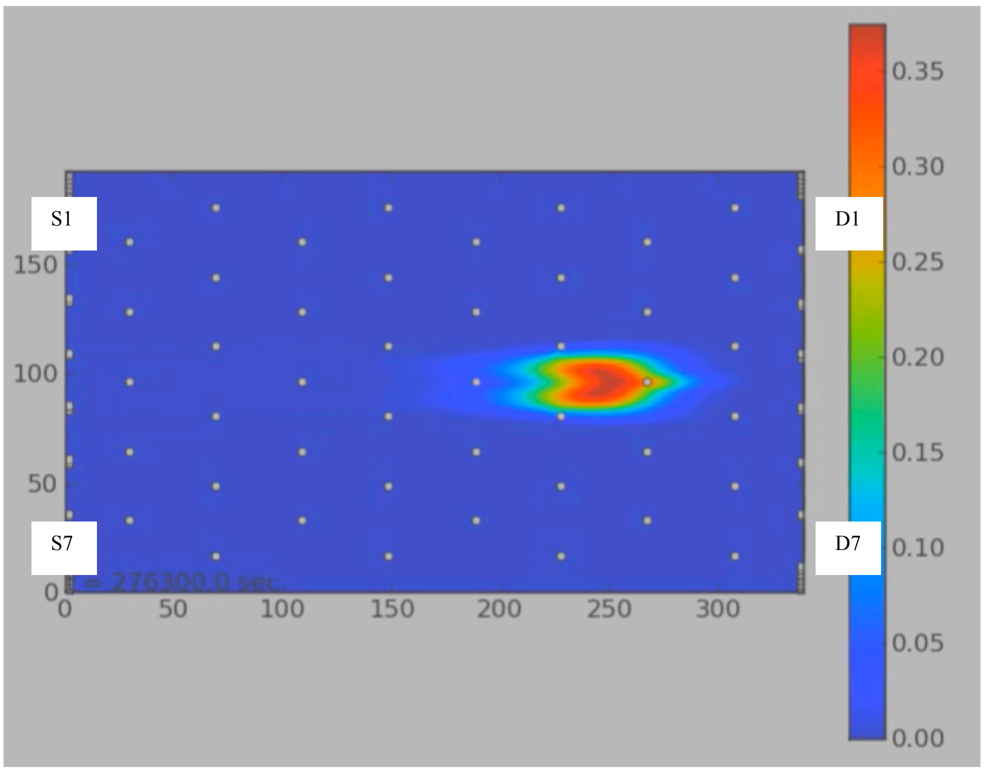


Figure 6: Animation of MT3DMS model of a centerline tracer plume. This snapshot is 76.5 hours after tracer introduction into reservoir S4. The white circles are well locations. The color scale is normalized concentration (C/C_0).

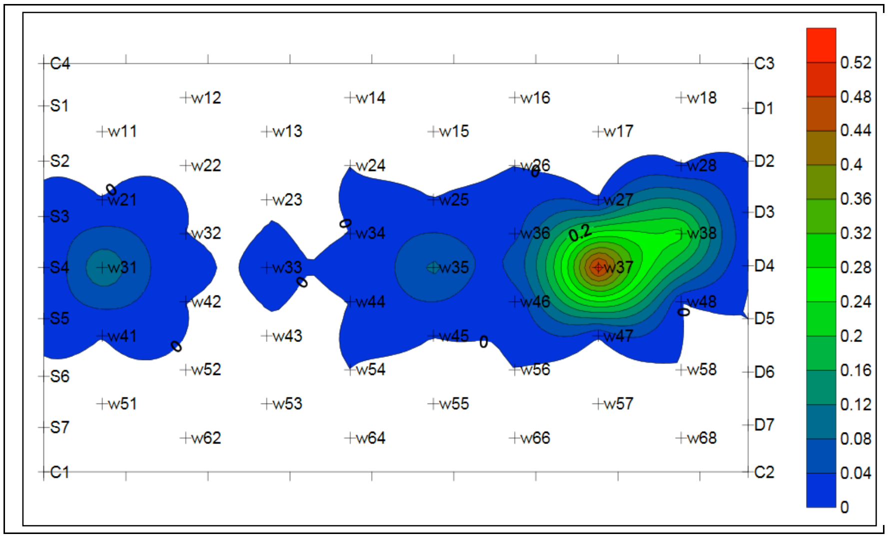


Figure 7: Contour plot of normalized NaBr tracer concentration (C/C0) obtained by kriging measurements taken with EC sensors. Centerline plume, 76.5 hours after tracer introduction.

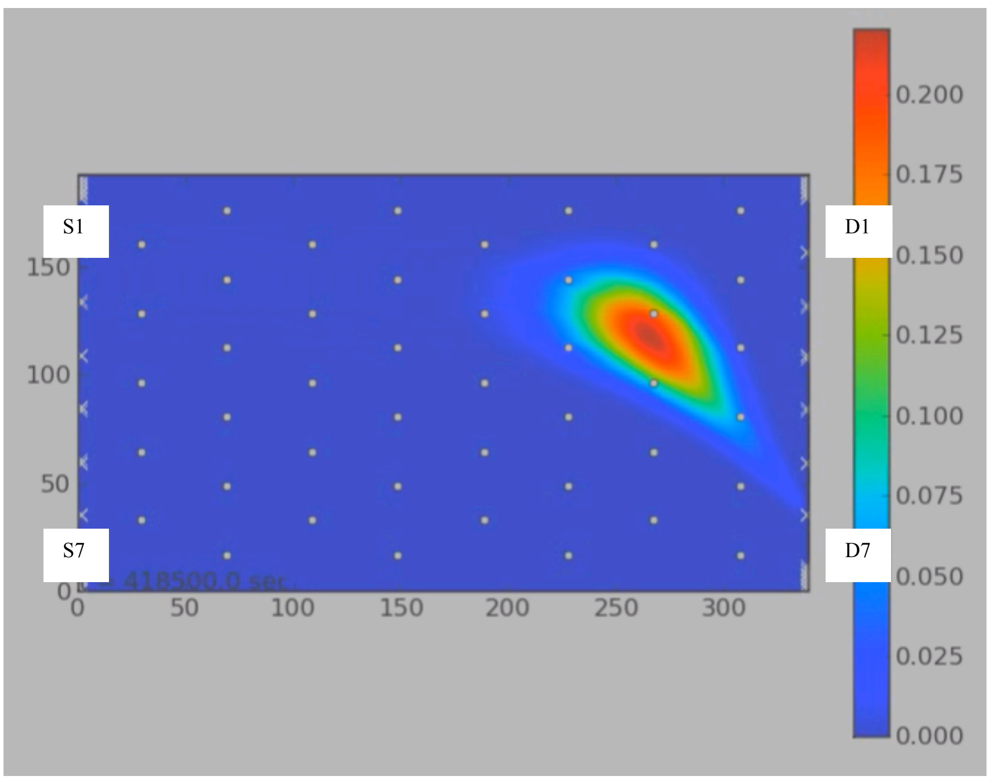


Figure 8: Animation of MT3DMS model of the “diagonal” tracer plume. This snapshot is 116 hours after tracer introduction into reservoir S2. The white circles are well locations. The color scale is normalized concentration (C/C_0).

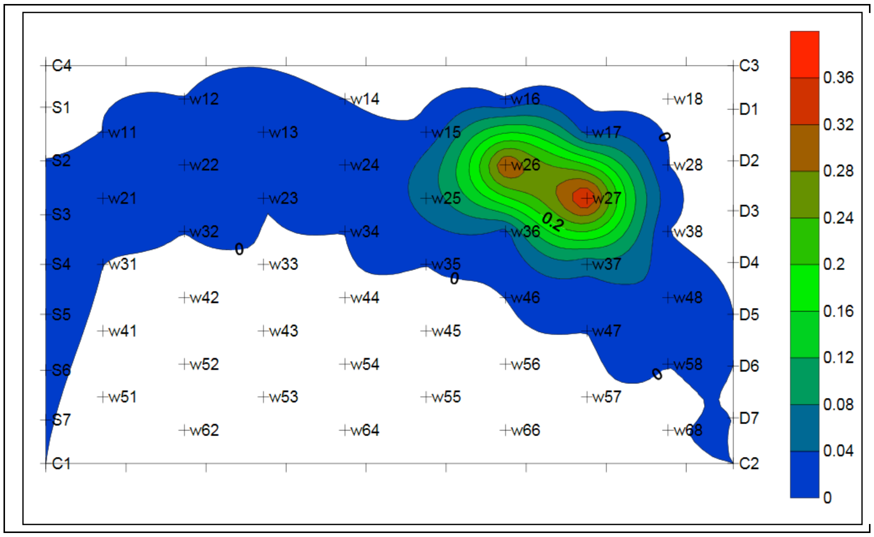


Figure 9: Contour plot of normalized NaBr tracer concentration (C/C0) obtained by kriging measurements taken with EC sensors. "Diagonal" plume, 116 hours after tracer introduction.

Figures 10 and 11 compare the numerical and physically measured plume concentrations for a bi-modal plume configuration. The bi-modal plume was created by opening all 7 supply and 7 drain reservoirs to flow. Four non-porous zones were created by placing boxes constructed of PVC sheeting in the synthetic aquifer media; similarly, non-porous zones were created in the numerical model. A single mode plume was released from reservoirs S3, S4, and S5. The plume was split by the first non-porous obstruction. The two plume lobes traveled around the second, wide obstruction and recombined into a single mode again down gradient.

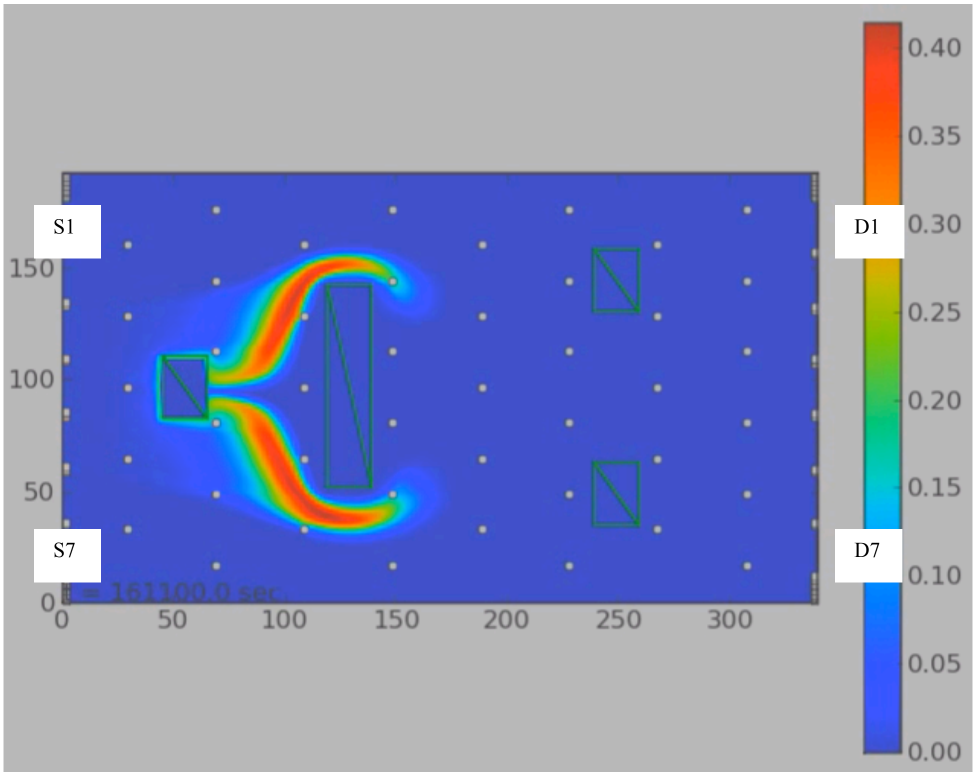


Figure 10: Animation of MT3DMS model of the tracer plume with non-porous regions. This snapshot is 45 hours after tracer introduction into reservoirs S3, S4, and S5. The white circles are well locations. The color scale is normalized concentration (C/C_0).

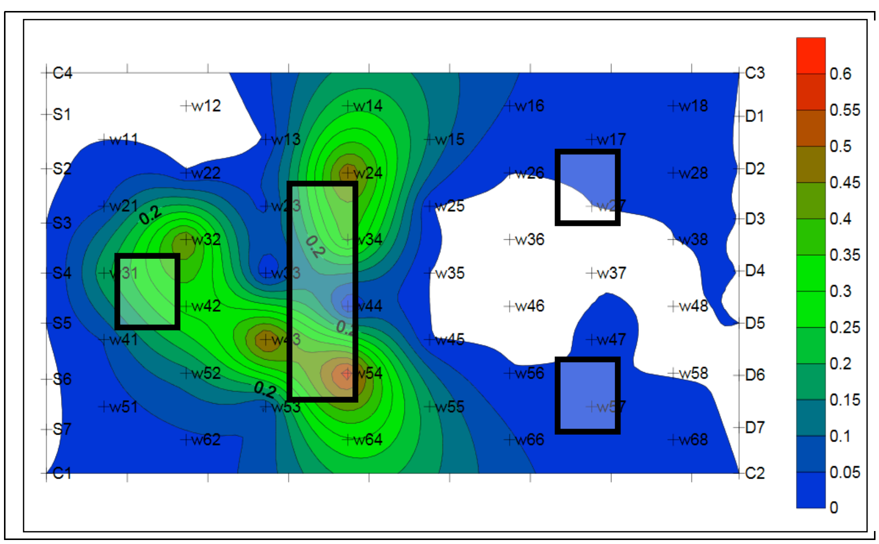


Figure 11: Contour plot of normalized NaBr tracer concentration (C/C0) obtained by kriging measurements taken with EC sensors. Non-porous regions plume, tracer introduced in S3, S4, and S5, 45 hours after tracer introduction.

Model Calibration

Comparison of plume transport model results to measured tracer data indicated the need to calibrate the transport model input parameters of grid-scale dispersivity and porosity. A transport model calibration method was developed suitable for application to a wireless sensor network and automatic model calibration system. The calibration methodology uses temporal method of moments analysis to characterize experimentally measured breakthrough curves. Calibrations were performed on the centerline plume configuration and the resulting parameter estimates were used as inputs in predictive numerical models of the other plume configurations. The results of these predictive models are compared to experimental results.

Flow model calibrations employed the numerical tool UCODE linked to a forward model of the synthetic aquifer created in MODFLOW for the purpose of determining hydraulic conductivity. Hydraulic heads and volumetric outflow were used as measured observations for the flow model calibrations. It was assumed that the calibrated flow models were valid and appropriate to use as input to the MT3DMS solute transport models. The calibration of solute transport models therefore use MODFLOW results as an input to MT3DMS.

Three input parameters were involved in the solute transport model calibration: grid-scale longitudinal dispersivity (α_{L-grid}), grid-scale transverse dispersivity (α_{T-grid}), and porosity (Φ). Temporal method of moments analysis was applied to EC sensor data to calculate two observation values per each well, these observations were: center of mass transport time (μ_1') and breakthrough curve scale dispersivity (α_{BTC}).
Absolute temporal moments are then defined as (Govindaraju and Das, 2007):

$$\mu_n = \int_0^\infty t^n C(z,t)dt \qquad (1)$$

where μ_n is the absolute temporal moment of order n, t is time, and $C(z,t)$ is solute concentration as a function of a length variable z and time. Normalized moments are defined as:

$$\mu_n' = \frac{\mu_n}{\mu_0} \qquad (2)$$

and central moments as:

$$m_n = \frac{1}{\mu_0}\int_0^\infty (t-\mu_1')^n C(z,t)dt \qquad (3)$$

The zero order moment (when the subscript n = 0) equates to the total mass, and for a conservative solute tracer the normalized zero[th] moment $(\mu_0') = 1$, that is mass is conserved. The first normalized moment is a measure of the center of mass. For temporal based moments applied to BTC, as discussed here, the first normalized moment is the travel time of the center of mass for that BTC. The second normalized moment can be expressed as:

$$m_2 = \mu_2' - (\mu_1')^2 \tag{4}$$

which is equivalent to the definition of the variance for a random variable. Following the derivation of Butters and Jury (1989), the coefficient of variation (CV) is:

$$CV = \left(\frac{\mu_2' \mu_0'}{(\mu_1')^2} - 1\right)^{\frac{1}{2}} \tag{5}$$

and the dispersivity localized to the BTC is:

$$\alpha_{BTC} = \left(\frac{z}{2}\right)(CV)^2 \tag{6}$$

In the synthetic aquifer the length scale term (z) was set equal to the longitudinal distance from the inlet to the center of the well.

Two temporal moments terms were used to characterize BTC measured in the synthetic aquifer. The first normalized moment (μ_1') is a time scale measure of how long it took for the BTC center of mass to travel from the inlet to the well where the concentrations were measured. The BTC dispersivity term (α_{BTC}) is a measure of dispersivity scaled by longitudinal distance, localized to the specific well. Employing these two characteristics as observations in transport model calibration is convenient because they provide a measure of two distinct physical quantities related to both advection and dispersion.

Comparisons of experimentally measured to numerically modeled BTC are seen in Figure 12. The numerical model results are from a calibration employing observations from 10 wells for the centerline plume configuration. Figure 12 presents BTC measured in the centerline wells.

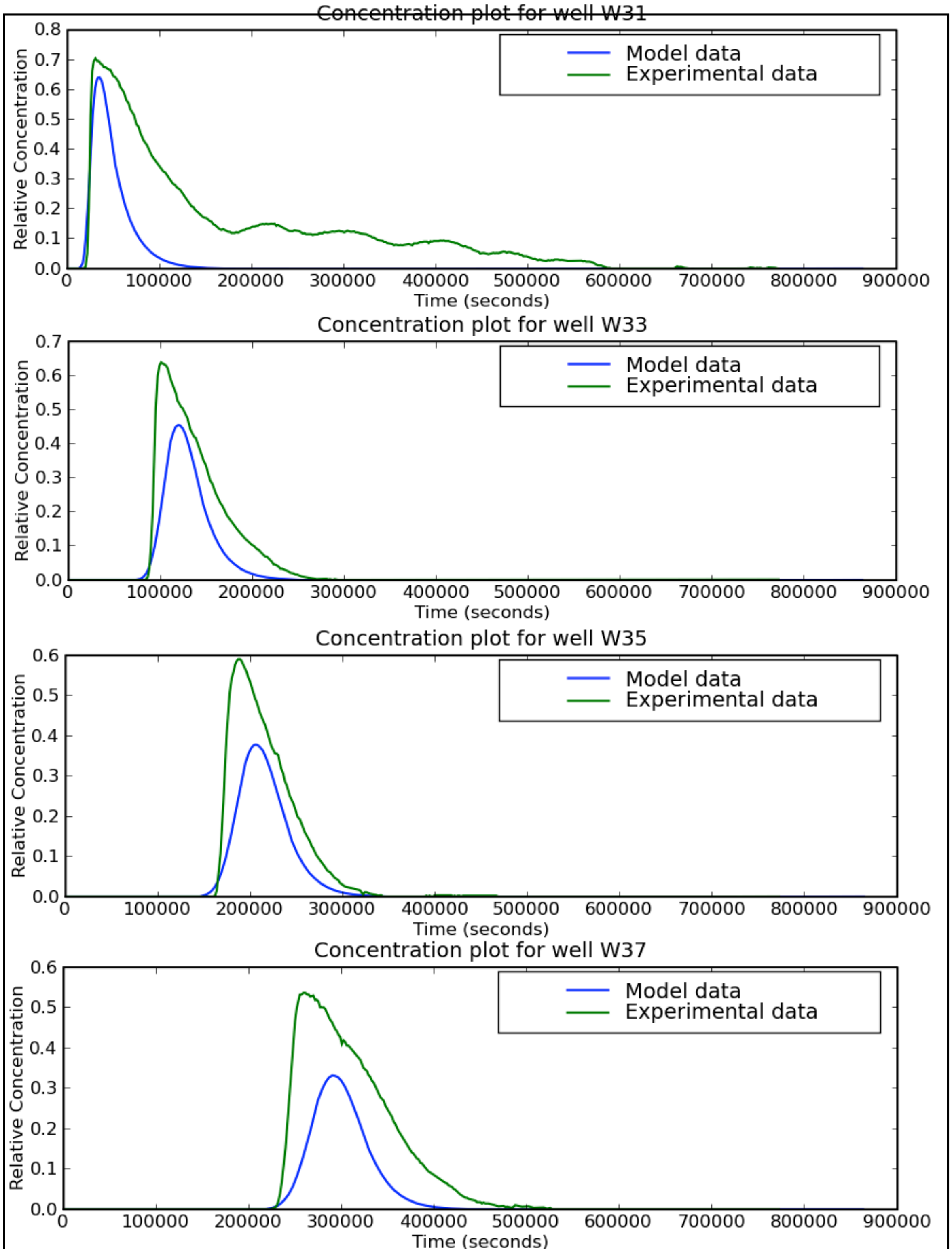


Figure 12: Comparison of experimental to model data BTC, centerline wells, centerline plume configuration.

Installation of Crossbow and TelosB Motes in Tank

We have successfully installed the WSN TelosB and Crossbow motes into the experimental test bed and are currently using the WSN for data collection, see Figure 13. To save money on the number of motes that needed to be purchased, we built "break-out" boxes which multiplex multiple sensors for each mote, see Figure 14. We have tested different networking, duty-cycling, and time-synchronization algorithms to determine which work best for this application.

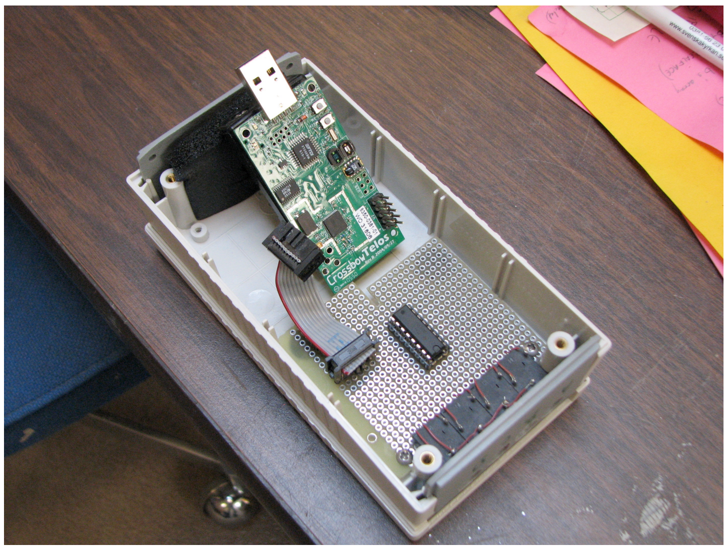


Figure 13: Motes installed in tank break-out boxes which shield the motes and multiplex up to four sensors per mote.

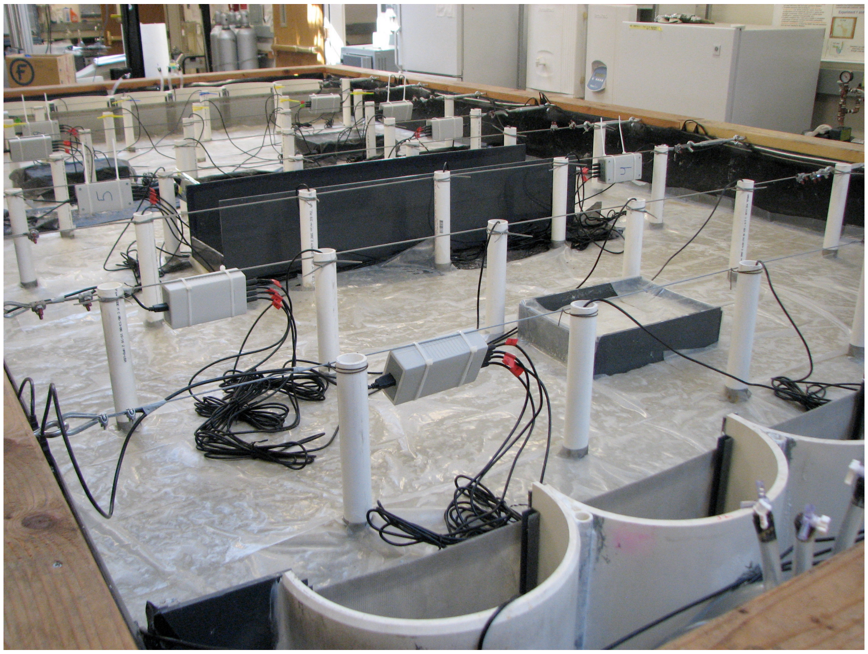


Figure 14: Inside of break-out box.

5.2 Virtual Sensor Network Based Closed Loop System

Imposing some structure within the sensor network to effectively achieve application objectives is an attractive option for the self-organization of large-scale and collaborative WSNs. Virtual Sensor Networks (VSNs) is an emerging concept that supports collaborative, resource efficient, and multipurpose sensor networks that may involve dynamically varying subset of sensors and users (Jayasumana, Han, and Illangasekare 2007). Realization of VSNs requires design and implementation of many algorithms and protocols. During the first two years of the project we proposed a compound solution that combines clustering, cluster tree based routing, and a cluster tree based VSN membership discovery scheme to addresses the VSN formation and data delivery problems. As the final step, we demonstrated the ability of VSNs to meet the application requirements of subsurface plume tracking by simulating a closed loop system. Below we discuss the motivation, design of the closed loop system, and simulation results.

Concentration of subsurface plumes can change within several days; however, they tend to migrate very slowly. Therefore, it is desirable for nodes that are immersed in the plume to sample more frequently while other nodes to sample less frequently. Energy can be saved by reducing unnecessary sampling and sleeping in the meantime. When a plume migrates to a different area, a new set of nodes will be frequently active allowing previously active nodes to reduce their sampling rate and sleep for a longer time. Use of different sampling schedules at different network segments could result in unreliable data forwarding paths as intermediate nodes may decide sleep, if they do not detect the

phenomenon. Such inconsistent routes could result in packet delays or drops and could consequently affect the accuracy of transport models as the data fed into them may be stale. Hence, it is important to keep relevant nodes active to ensure consistent forwarding of data to the base station. Based on the end user interests or predicted behavior from the transport models nodes can be command to increase/decrease the sampling rate to track the plume with high spatial and temporal resolution. Such a system requires the ability to send commands such as sample *faster*, *slow*, and *now* into the nodes as well as receive data from the nodes. Therefore, we envision future subsurface plume tracking systems to be developed as closed loop systems.

VSNs can facilitate aforementioned requirements while reducing power consumption and ensuring relevant nodes stay active. VSN based multicasts and broadcasts can be used to effectively deliver commands from the processing center into a large group of nodes. We simulated a closed loop plume monitoring system to demonstrate the efficacy of our cluster tree based VSN formation scheme.

Figure 15 shows the design of the simulated closed loop system. We coupled a VSN enabled sensor network and a plume transport model. The simulated VSN is formed according to the cluster tree based self-organization scheme developed in 2007/2008. Set of nodes were ground into a cluster and clusters were then connected together through a cluster tree. The base station, i.e., the root of the cluster tree, connected rest of the network to a system that model and predict the behavior of plumes. Initially all the nodes had the same sampling rate. If the detected chemical concentration is beyond a certain threshold, the node was considered to be in the plume and its sampling rate was increased. Such nodes send the concentration data all the way up to the plume modeling system and at the same time formed/joined a VSN. Such nodes continued to report their concentration values, if new sensor reading is substantially different from the previously reported value. Based on new data, transport and prediction models continued to evolve. Based on the predicted behavior, nodes werecommanded to change their sampling pattern to track the plume with high spatial and temporal resolution. Such commands were delivered to a node or set of nodes through the VSN (arrows pointed downwards in Figure 15). The VSN changed the active schedule of the intermediate cluster heads to match the new sampling rate, while forwarding such messages. This ensured a consistent path towards the base station and hence will not drop or delay messages. We simulated a system that delivered both the data and the prediction related commands. However, depending on the application scenario and use requirements other commands can be incorporated into a VSN.

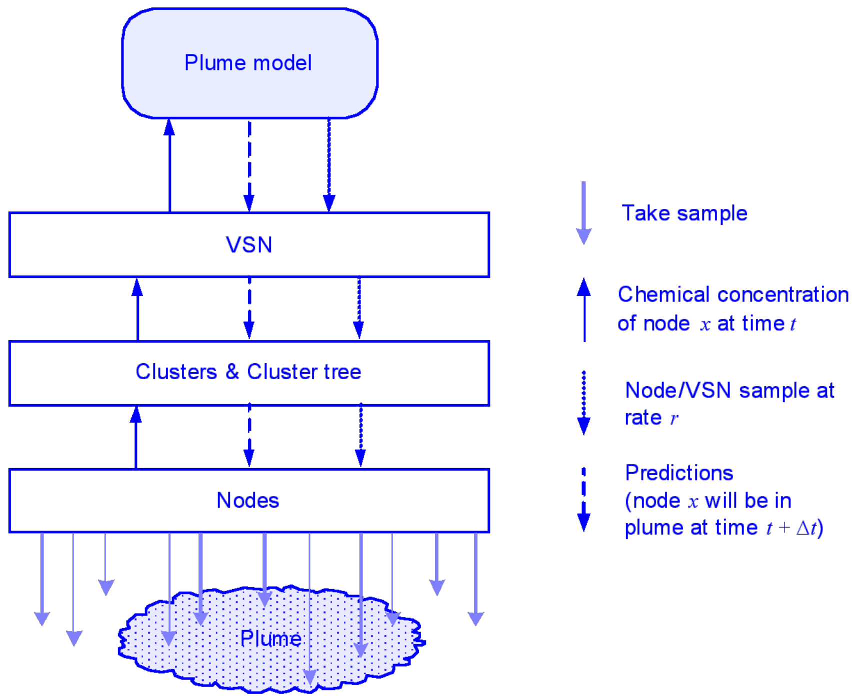


Figure 15 – Different layers and their interactions in the simulated VSN based closed loop system. Direction of Black arrows indicates direction of data flow (Bandara 2008).

A synthetic data set was used to simulate two migrating plumes that merge together (Figure 16). Specific details of synthetic data generation are given in (Barnhart 2008). Synthetic data set was generated for a $200m \times 350m \times 15m$ sensor filed and it was scaled up to $1000m \times 1750m$ and positioned in the middle of a $2000m \times 2500m$ sensor field. To simplify the analysis, the 3-D data set is converted to a 2-D data set by taking average along the *Z*-axis. 1000 sensor nodes were randomly placed on the sensor filed. Three simulation scenarios were considered. The first scenario simulated a conventional WSN where all the nodes sample once a day. Second scenario simulated a VSN that delivered only the data to the transport model while the third scenario simulated a closed loop system that forwarded both data and commands. In both these scenarios, nodes sampled once a day if they were detecting sufficient chemical concentration otherwise sampled once in every two weeks. Cluster members were active for two seconds while cluster heads were active for 25 seconds to maintain the cluster tree and to diminish issues related to clock skew. We used the same synthetic data for the predictions as the transport model was not fully functional by the time we simulated the system. Predictions were issued once in eight weeks and valid for the next eight weeks. We simulated the migration of the two plumes over three years (1095 days). An ideal wireless network with no packet loss, delayed packets, corrupted packets, and collisions was assumed. Simulation parameters are based on Decagon 5TE sensors (Decagon Devices, Inc.) and TELOSB (Crossbow Technology) sensor motes. We assume nodes have a transmission range of $100m$. Detailed simulation setup and parameters are given (Bandara 2008). Simulation results are based on 100 samples.

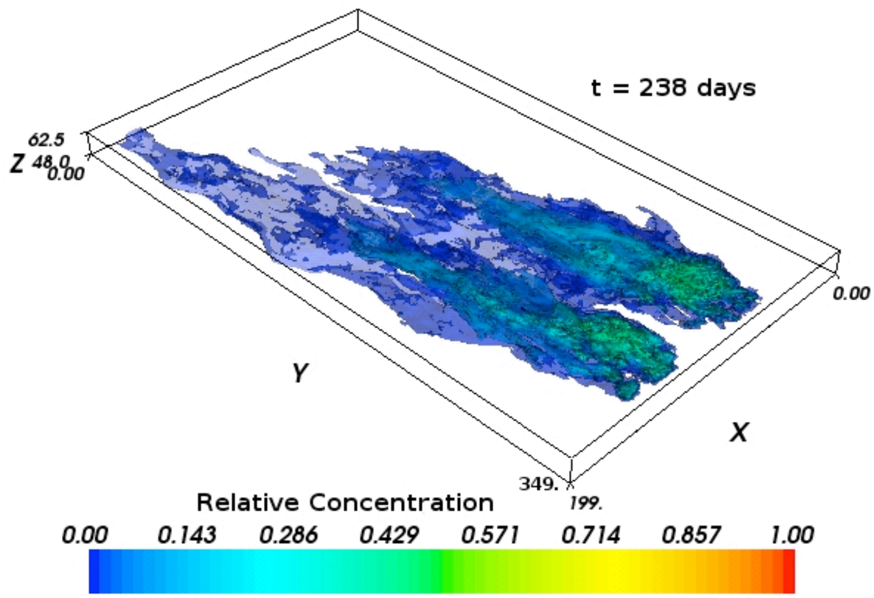
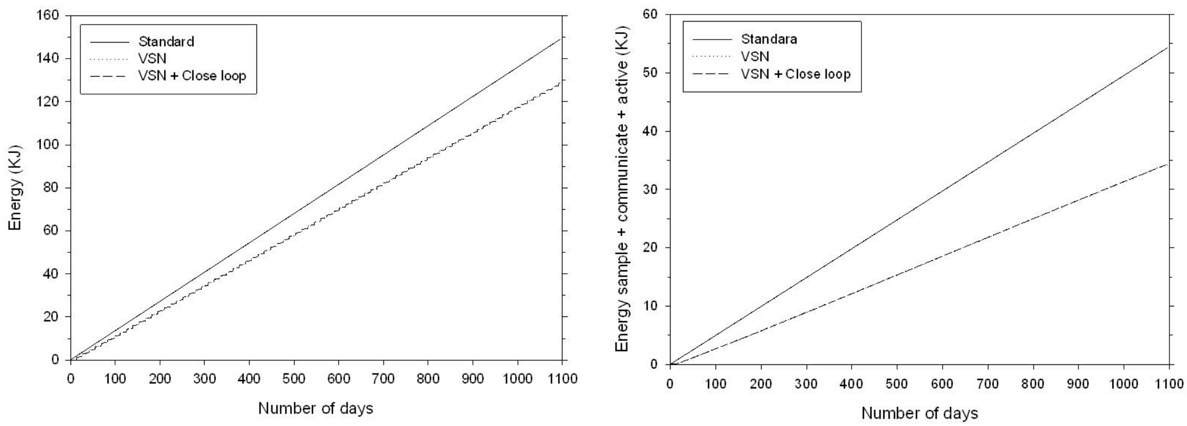


Figure 16 – Position of two migrating plumes at day 238 (Barnhart 2008).

Figure 17(a) shows the total energy consumption over three year period for the given simulation setup. Both cluster tree based VSN schemes are able to reduce total energy consumption by ~20KJ (37%). This is achieved by allowing nodes that are not in a plume to sample slower. Active to sleep power ratio is 3000:1; however, node duty cycle is 2/86400 (or 2/1209600 if samples in every 14 days) for a cluster member and 25/86400 for a cluster head. Hence, sleep power dominates in such slow evolving phenomenons that are monitored over several years. This is the reason that we do not see a significant performance improvement in Figure 17(a). Nevertheless, actual overhead of a VSN system depends on node's active, sampling, and communication power consumption. Therefore, we analyze the incremental power consumption by the simulated network in Figure 17(b). The ~20KJ energy saving is clearly visible and contributes to a 37% improvement over the standard network, i.e., the conventional WSN. VSN enabled closed loop system consumes more energy than the VSN only system, because of the commands that are send to the nodes. Energy difference between the two cluster tree based VSN schemes is small therefore two graphs are overlapped in Figure 17. Figure 18 shows the amount of data transferred in the system. Closed loop system has a relatively higher overhead because of the commands send to nodes based on the predicted behavior of the plume. Nevertheless, these predictions were useful in reducing the number of missed events therefore we were able to capture the behavior of the two plumes more accurately. Initially, all the nodes in the network report to the transport model to indicate their presence in the network hence accounts for the initial ~50KB of data. These results confirm the ability of the closed loop system to track the relevant phenomenon with high spatial and temporal granularity without incurring significant overhead. We further analyzed the applicability of our approach to fast moving phenomenons such as hazardous gases. We simulated a fast moving phenomenon by speeding up the plumes and simulating it over 3.5 days. Sampling intervals were reduced to five and 30 minutes. We observed similar energy saving over the 3.5 days, which is significant given the short

time span. Though 37% energy saving is specific for the given simulation setup, it demonstrate the capability of VSNs to reduce the power consumption by adapting sampling rates.



(a) (b)

Figure 17 – (a) total energy consumed while tracking the plume, (b) incremental energy consumed while tracking the plume (Bandara 2008).

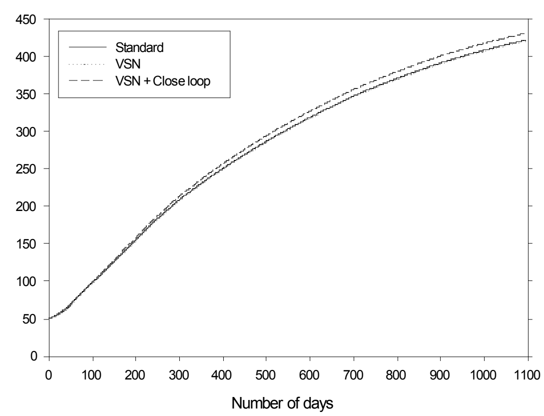


Figure 18 – Amount of data transferred between nodes and plume transport and prediction model (Bandara 2008).

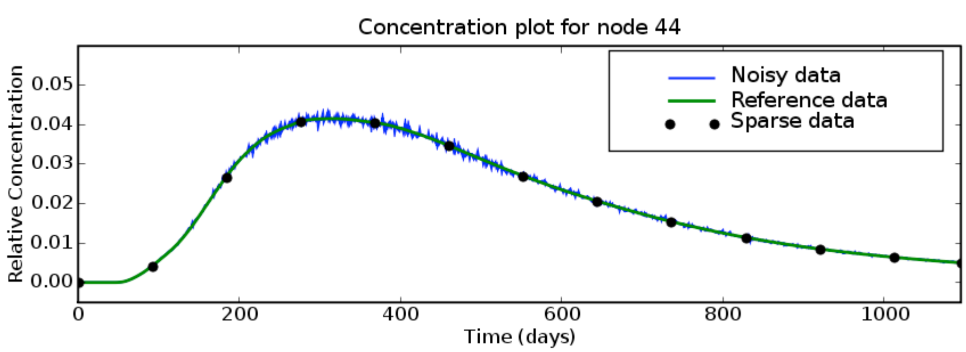
5.3 Parameter Estimation Investigations

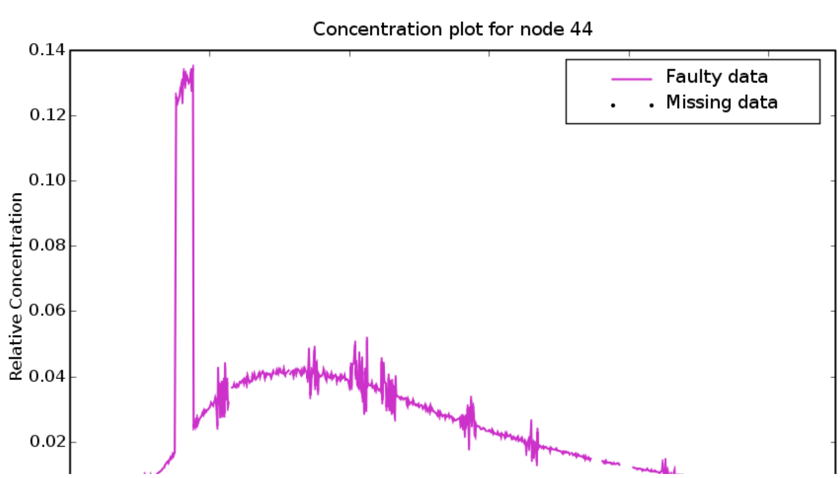
Though enticing, initial investigations into using WSNs for surface and subsurface monitoring suggest (including this one) that sensor and network technology maturation is compulsory before water quality and quantity can be accurately monitored and predicted. These studies invariably report the collection of considerable amounts of anomalous data due to drifting sensor calibration, faulty electronics, and unforeseen transient environmental conditions. Hence, though a WSN is capable of monitoring and measuring the environment at scales, locations and resolutions not before possible, it poses

enormous data analysis and management challenges. Further investigations should be prudently conducted in controlled simulative and laboratory environments prior to field deployment where poorly quantified uncertainties often dominate results.

Increased availability of computer resources has been instrumental in the almost ubiquitous use of computational models to calculate health risks, design cleanup strategies, guide environmental regulatory policy, and determine culpable parties in lawsuits. Such use culminates in computational models dramatically influencing environmental decisions involving large investments of effort and funds. Given this, it may be surprising that few studies exist designed to establish model credibility. There is a growing belief that models will become more effective if model parameters are periodically updated or re-calibrated as new data becomes available. However, the effect that erroneous data may have on simulation results is largely overlooked -- especially in light of the above pioneering WSN studies.

We performed a study which focuses on the periodic inclusion of concentration data into a computational advection-dispersion transport model. The data is synthetically generated and a WSN simulator is used to inject authentic anomalies into the data set. Data assimilation (see Figure 19) is considered using four scenarios: (i) infrequently collected data with minimal noise, (ii) daily WSN data containing only theoretical noise levels according to sensor specifications, (iii) data containing WSN faults (including noise), and (iv) data with fewer WSN faults due to the use of a WSN fault detection application. The presented methodologies employ modeling tools commonly accepted in industry (i.e., MODFLOW-2000, MT3DMS, and PEST). Thus, the aim is to provide practical insight into the directions of future modeling efforts in a new data context.





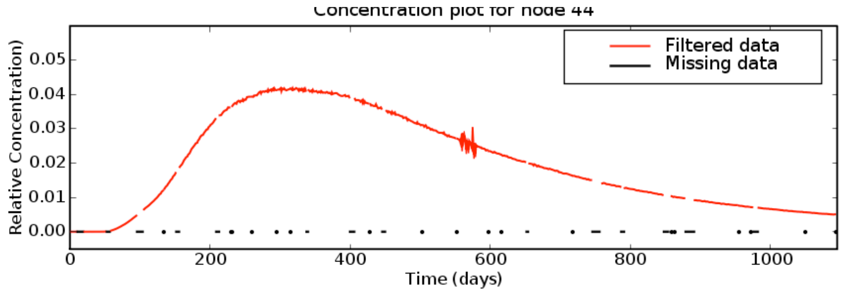


Figure 19 – Example breakthrough curve data used for model calibration.

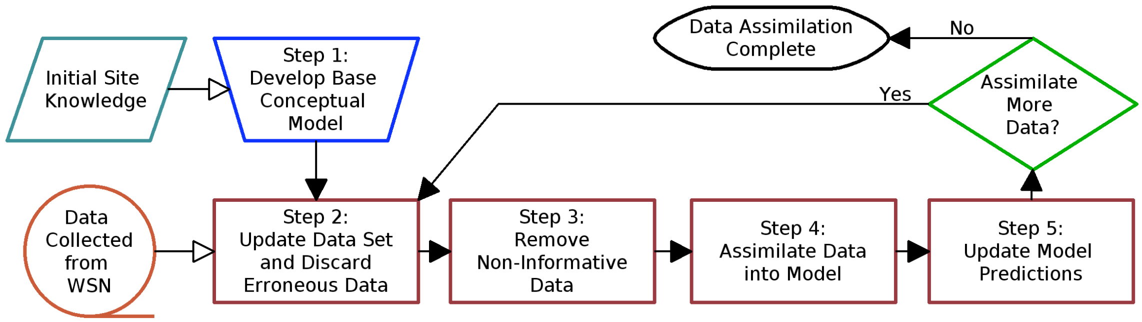


Figure 20 – Simple data assimilation procedure.

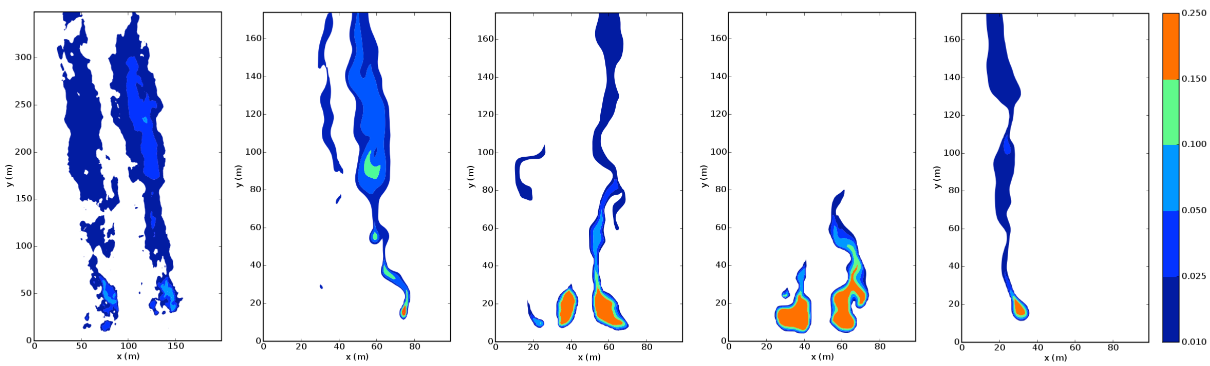


Figure 21 – Reference model (first plot) versus predictive snapshots of relative concentration using the noisy, faulty, filtered and sparse data sets, respectively, at day 672 of the simulation.

A complex three-dimensional synthetic model was developed using field site measurements (see Figure 16) and, from this, four data sets were constructed to mimic different scenarios. A simple data assimilation methodology (see Figure 20) was employed to calibrate a two-dimensional numerical transport model and subsequent model predictions were compared to the reference data set. This investigation concluded with the following suggestions and remarks:

- Even small amounts of erroneous data may significantly affect the outcome of the calibrated model (see Figure 21). While a fault detection service may remove a majority of these abnormalities, manual inspection of data may still be advisable. Furthermore, satisfactory parameter estimation results do not guarantee reasonable model predictions if faults persist. When statistics of data faults, such as random noise, can be estimated *a priori* then regularization techniques may be used to ensure robust solutions.
- Transport model forecasts are highly sensitive to parameter estimation input variables, particularly regularization parameters. Although PEST includes many

features to induce robust parameter estimation and model inversion, expertise is needed to achieve reliable results. Parameter estimation software should be viewed as another component in the modeling process which contributes to the overall model error and for which credibility should be sought.

- Model agreement generally improves with each iteration of data assimilation even when most previous data has been eliminated through data reduction. This iterative approach to parameter estimation may be appropriate whenever transient data is available.
- Predictions of transport fate only remain valid for short time periods after model calibration despite the increase in data. This advocates that data assimilation and wireless networks be left in place during the entire field study.

Finally, the results suggest that contaminant transport models will benefit as *in situ* sensing and network technologies mature. It is imperative that existing modeling tools must be adapted and new approaches should be developed in order to efficaciously assimilate WSN data.

We have worked on a new method to do this. Instead of using concentration data, see Figure 22, we instead used the frequency information, see Figure 23, from the breakthrough curve profiles in our parameter estimation process. This guarantees faster and more reliable model inversion.

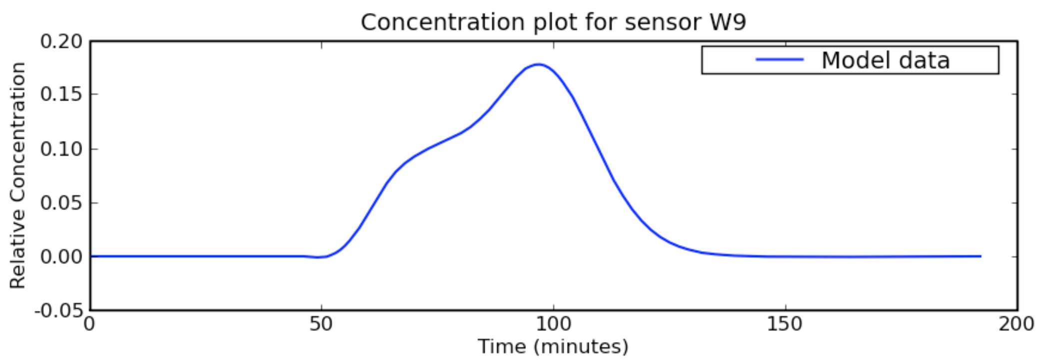


Figure 22 – Example breakthrough curve data used for model calibration.

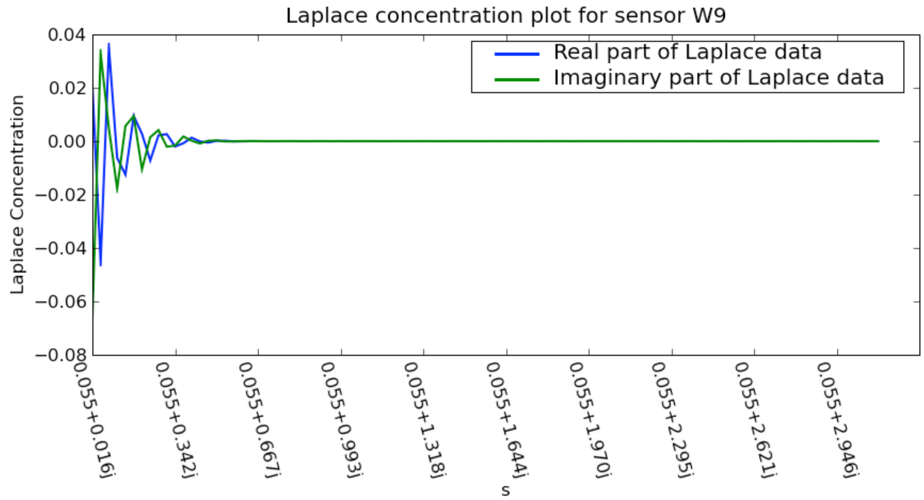


Figure 23 – Frequency information taken from Figure 19 and found using a numerical Laplace transform.

6. Project Conclusions and Suggestions for Future Work

6.1 Laboratory and Numerical Modeling Conclusions and Suggestions

Lessons Learned and Recommendations

The key lessons learned during the course of this investigation and corresponding recommendations are:

- The operation of a synthetic aquifer requires continual maintenance and care. Daily degassing of the supply lines was required along with filtering and filling of the supply tank. Prevention of bio-film and algae growth required frequent attention. If tap water is used as the supply source, it is recommended that it is monitored closely for seasonal changes in composition.

- Small changes in synthetic aquifer outflow rates were noticed, these were most likely due to changes in ambient laboratory temperatures. The synthetic aquifer has a sand and water weight of over 8 tons, which is a considerable thermal mass. Changes in ambient temperatures would cause a slowly changing temperature distribution within the aquifer, which intern could be cause of some of the heterogeneous effects observed. Maintaining a constant ambient temperature of the synthetic aquifer and the supply water is recommended to reduce variability.

- Sensor calibrations are critical to obtaining accurate data; however it is often difficult to obtain absolute value precision from sensors. Often they perform better at measuring changes and change rates, therefore applying relative measurement scales is frequently more advantageous than using absolute scales. For WSN applications an absolute sensor measurement scale is preferred because it provides a baseline for comparison. It is recommended that WSN employ an absolute value reference adjustment to all sensors. This could be accomplished electronically if the sensors prove to be sufficiently robust or it could be accomplished by placing each sensor in a control solution for a reference reading prior to site installation.

- The EC sensors used in this study required some break-in time. Whenever a sensor was moved from one well location to another, the first 2 or 3 readings were typically low and these data points were ignored. Also, spikes in the sensor data occurred frequently when the sensors were new but then diminished over time. Allowing sensors to acclimatize to a steady state condition prior to beginning an experiment is recommended.

- Homogeneity is a useful concept but it rarely occurs, even in tightly controlled environments. Account for variability in any system.

- WSN data analysis procedures must account for drifting and faulty data. A WSN must make use of protocols which can identify background or sensor drift and account for the time rate of drift. Faulty sensor data is going to occur at some point in any WSN application, therefore protocols should be prepared for when they occur and ensure they do not skew the data set.

- Plume shape and transport behavior can be effectively manipulated by fluidic control in a homogeneous media. The 7 supply and 7 drain reservoirs in the synthetic aquifer enabled the creation of several complex plume configurations. The creation of a single mode plume which split and later recombined did however require the addition of non-porous inclusions into the aquifer field.

- Fluid density differences in open hole wells have a considerable influence on the depth-wise aqueous concentration distribution within the well. Long term emplacement of sensors will have to account for possible density driven distributions. Sensors located at multiple depths within a single well may be required to accurately assess the mass of a contaminant.

- Temporal method of moments analysis shows promise as a method to characterize BTC in a global sense for use in automated calibrations. It is recommended to add the zeroth moment to calculate mass and higher order moments to provide more information on BTC characteristics.

- Temporal method of moments looks to be particularly useful in laboratory scale experiments when time scales are on the order of days or weeks, and data analysis can be conducted after the BTC has passed through a well. Field applications may not have the luxury of complete BTC. This method also is ill suited to real-time calibrations because it requires a complete BTC for

global characterization. Point source concentrations in combination with spatial moments characterization may prove more applicable to WSN deployment at the field scale.

- The WSN may prove to be an appropriate data collection technology for the field once protocols are developed in this more controlled setting. Robust data collection and fault detection algorithms will be absolutely necessary for the deployment in the field.

Recommendations for Future Studies

The study presented here was a continuing step towards the goal of building autonomous plume monitoring networks of sensors which communicate wirelessly and have the ability to make predictive evaluations of plume transport. Before such a system will be ready for field deployment, many cross-discipline advances need to be made.

Data quality protocols need to be investigated which can distinguish desirable "real" data from drifts, faults, or sensor errors.

This investigation performed flow model and transport model calibrations completely separate from each other. A next step in WSN technology development would be to conduct physical experiments and concurrent modeling studies which perform coupled calibrations of flow and transport; with a further goal of conducting real-time calibrations based on multiple types of observation data, (i.e. heads, flows, concentrations, etc.).

The experiments conducted in this study were essentially static in nature. Adding a dynamic component would provide a formidable test of WSN capabilities. The addition of transient well pumping or injection or transient changes to the flow boundaries could be used to add this dynamic aspect to the problem.

WSN promise near immediate access to field data at high levels of temporal and possibly spatial resolution; however the data provided by sensors may not be as accurate as data obtained by traditional sampling means. It is therefore proposed that a cost-benefit analysis be conducted to ascertain the financial and technical implications of employing a WSN which provides less accurate but high resolution data compared to using traditional sampling methods. For critical situations where contaminants risk human health and safety, accuracy will be of primary importance; but for site assessments and monitoring situations, WSN data and predictions have the potential to provide more information at a lower cost.

6.2 Virtual Sensor Network Based Closed Loop System Conclusions and Suggestions

Imposing some structure within the sensor network to effectively achieve application objectives is an attractive option for the self-organization of large-scale and collaborative WSNs. We developed the conceptual architecture for virtual sensor networking, which

allows some of the nodes in the network (e.g., those immersed in the plume) to collaborate on sensing, detecting, and tracking tasks (Jayasumana, Han, and Illangasekare 2007). The architecture relies on underlying networking protocols to support connectivity among members of the VSN. We adopted a clustering based VSN formation approach that can effectively meet the application requirements of subsurface plume monitoring while conserving energy.

We presented a configurable cluster and cluster tree formation algorithm that is independent of network topology and does not require a-priori neighborhood information, location awareness, or time synchronization (Bandara and Jayasumana 2007). Configurable parameters of the algorithm can be used to form cluster trees with desirable properties such as controlled breadth and depth, uniform cluster size, and more circular clusters. Message complexity of the algorithm grows linearly with the number of nodes in the network, therefore algorithm scales well into large networks. Two-step, post cluster optimization phase is further proposed to increase the connectivity of the network and to further reduce the depth of the cluster tree (Bandara 2008). Simulation based analysis shows that the algorithm forms more circular and uniform clusters, a cluster tree with lower depth, and more importantly forms a more ordered structure in the network. Cluster and tree properties are comparable with hexagonal packing particularly for lower transmission power levels and sparse networks. The structure imposed by the algorithm makes it applicable to broad classes of applications.

The proposed cluster tree based routing strategy facilitates both node-to-sink and node-to-node communication (Bandara 2008; Bandara and Jayasumana 2009). Hierarchical addresses that reflect the parent-child relationship among cluster heads are used to route data along the cluster tree. Such hierarchical addresses significantly reduce the amount of state need to be maintained at cluster heads. Two extensions of the routing scheme, cross-links and circular-paths based routing, increase the number of messages delivered by the network by 2.1-2.4 and 5.2-6.4 times, respectively. Under ideal conditions, our approach guarantees delivery of events/queries and has a lower overhead compared to routing strategies such as rumor routing and ant routing. The cluster tree formed by our algorithm is used to identify and form virtual sensor networks (Bandara, Jayasumana, and Illangasekare 2008; Bandara 2008). Our implementation of VSN is able to deliver unicast, multicast, and broadcast traffic among nodes observing similar events, efficiently. Efficacy of the VSN based approach is demonstrated by simulating a closed loop subsurface chemical plume monitoring system (Bandara 2008). The algorithm is further extended to support the formation of a secure backbone that can enable secure communication among nodes and users of collaborative sensor networks (Bandara, Jayasumana, and Ray 2008).

Our simulation results are encouraging and confirm the appropriateness of cluster tree based VSNsfor large-scale subsurface plume monitoring systems. Though clustering algorithm, secure backbone formation algorithm, cluster tree based routing schemes, and VSN formation algorithm are designed for the plume tracking application these algorithms/schemes are applicable for broad class of problems. These schemes are also scalable hence suitable for actual field implementations. Therefore, we believe contributions of this research will have a much more profound impact in future collaborative and large-scale WSNs.

As a starting point towards virtual sensor networks, we designed a set of solutions that facilitate some of the fundamentals requirements of VSNs. However, realization of VSNs requires design and implementation of many other algorithms and protocolsthat support merging and splitting VSNs. Though managing these events in resource constrained WSNs is not straightforward, these issues are critical and need to be addressed to achieve the full potential of VSNs. To test our algorithms for large-scale networks with thousands of sensors, we had to build our own simulation platform. By doing so, we did not implement/simulate the underlying data link layer. It is important to test the performance of our algorithms on a rigorous simulation platform such as TOSSIM and on an actual testbed such as moteLab before any field implementations. Though our routing extensions were able to deliver several magnitudes more messages, we realized that lot more energy remains in the network at the end of the network lifetime (i.e., until first node die). Therefore, it is important to research on further solutions that can utilize the residual energy available inrest of the network. In the proposed plume tracking system, motes will stay on the surface while only the sensors are deployed insidethe wells (Jayasumana, Han, and Illangasekare 2007). The surface sensor will have the opportunity to harness energy by having solar cells. Therefore, it is also important to determine to what extent that our scheme is able to prolong the network lifetime if nodes have such capabilities to harness energy.

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